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# CONCEPTS OF RADIOLOGICAL HEALTH. PART I. RADIATION PRODUCTION AND ABSORPTION. PART II. BIOLOGIC EFFECTS OF RADIATION ABSORPTION

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# Concepts of

# Radiological Health

Part I. Radiation Production and Absorption
Part II. Biologic Effects of Radiation Absorption

by

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Public Health Service
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## Purpose of the Concepts

The manual is addressed to public health administrators who, without special training in physics, recognize the importance of learning the elementary facts about the impact of the atomic age on health. Its purpose is twofold:

1) To provide a concise yet elementary discussion of radiological health.

2) To serve as a source book for Public Health Service Regional Consultants in preparing short lectures and brief courses in radiological health.

# CONCEPTS OF RADIOLOGICAL HEALTH

## Preface

The major goals of radiological health are to prevent impairment of human well-being from exposure to injurious ionizing radiations and to promote better health through the beneficial use of radiation, radiation-producing machines, and radioactive substances.

As a result of discussions by the Surgeon General, Public Health Service, Department of Health, Education and Welfare, with leading universities, with the Atomic Energy Commission, and with the Department of Defense, it has been decided that preparation of indoctrination courses and training courses in public health aspects of ionizing radiation and atomic energy are properly a responsibility of the Public Health Service.

These concepts have been prepared by the Radiological Health Branch of the Public Health Service to make available, in a single volume, viewpoints and basic information pertinent to the practice of radiological health. It employs lecture data and illustrative examples that have been used by personnel of the Radiological Health Branch in holding radiological health orientation courses.

The approach used may seem to some to verge on the naive, particularly in the sections on production, absorption, and biologic effects of radiation. The prime purpose of these presentations, however, is to help health workers develop perspective in what for most of us is a new field of science. Therefore, the simplification is believed to be justified. As applied public health experience in radiological health becomes more mature, there may be less need for simplified material. For the interim, this volume may serve as a source-book to aid in preparing elementary lectures and short orientation courses.

With this thought in mind, the subject matter has been divided into three parts believed logical for public health presentation:

I. Radiation Production and Absorption.

II. Biologic Effects of Radiation Absorption.

III. Radiological Public Health.

Part III will discuss the health implications of radiation exposure and the accepted public health measures for radiation protection. Part I and II are introductory in nature. They are included to furnish conceptual material on the origins of the several types of ionizing radiation, the mode of their absorption and some details about their biologic effects.

Experience has shown that the quickest road to understanding radioactivity and the biologic effects of ionizing radiations starts with development of a conversational vocabulary of radiation terms. Many health workers have been pleasantly surprised to discover that a mere working familiarity with these apparently technical words has removed, for them, much of the mystery surrounding radiological health. It is suggested that Appendix A, "Glossary of Radiation and Biological Terms," be read carefully at this point.

## CONTENTS


Part I Radiation Production and Absorption

A. Radiation -- A Public Health Problem

B. Atomic Physics and Isotope-Produced Radiations

C. Machine-Produced Radiation

D. Absorption of Ionizing Radiation

Part II Biologic Effects of Radiation Absorption

A. How Radiation Initiates Changes in Living Tissues

B. Units of Radiation and Radioactivity

C. Biologic Effects of Radiation

D. Some Radiological Health Implications

Part III Radiological Public Health

(In process of preparation)

## Part I: Radiation Production and Absorption

### A. Radiation -- A Public Health Problem

For centuries men of science have been working on problems concerned with natural phenomena and the structure of matter. About 400 B.C., Democritus, a Greek philosopher, proposed an atomic theory. In 1789, M. H. Kalproth, a German chemist, isolated metallic uranium. In 1897, Rutherford, a British physicist, distinguished between alpha, beta and gamma rays. In 1905, Einstein developed the concept of the equivalence of energy and matter. In 1919, Rutherford produced the first transmutation of elements by converting nitrogen into oxygen; and in 1939, Hahn, Strassman, Meitner, Frisch, Joliot, Szilard, Fermi, and others produced nuclear fission (atomic energy) in the laboratory. On December 2, 1942, at the University of Chicago, the first self-sustaining nuclear chain reaction was started; the release of atomic energy became a practical operation instead of an interesting scientific phenomenon; and the world supply of radioactive substances from being precious and rare suddenly became almost too common for comfort.

Although until after the atomic bombing of Hiroshima and Nagasaki in August, 1945, few knew of the success of the Chicago "atomic reactor", it marked the beginning of a new era. The atomic age, so introduced, brought with it promise of atomic power and many wonderful new radioactive substances useful in medicine, in industry, and in research. Atomic reactors and radioactive substances emit ionizing radiations that are hazardous to people, animals and plants. As organized society enjoys the benefits of the atomic age, its health authorities must assume the moral obligation of guarding the public health from harmful effects of ionizing radiations.

Everyone has read in newspapers, magazines, and books conflicting statements on the implications of the atomic age. We are told that (1) the devastation to be produced by uncontrolled use of atomic bombs, hydrogen bombs, and other atomic weapons will wipe out modern civilization, or (2) that the solving of the riddle of nuclear energy, by releasing unimaginable amounts of cheap power and by providing radioactive materials for use in medicine and industry, has opened a new era of comfort and material progress. Regardless of whether one is pessimistic or optimistic on this subject, ionizing radiations, nuclear energy, and use of radioactive substances in medicine and industry are here to stay. It is not a question of "Do we want them?" The question is "How do we live with them?"

Before the nuclear reactor was developed, man's sources of potentially harmful radiation were limited in number and power. There were available throughout the world for medical and other uses 3 pounds or so of refined radium, plus limited quantities of other naturally radioactive substances. There were numbers of diagnostic, treatment, industrial and experimental x-ray machines in hospitals, industries, and physicians' offices, and a few cyclotrons, Van de Graaff machines, and similar other mechanisms in experimental laboratories.

In those days, the hazards of radiation exposure were not of active concern to health authorities. Public health programs were preoccupied by the vast, urgent job of suppressing the mass killers, such as malaria, the dysenteries, and the contagious diseases. Relatively few people were associated with ionizing radiations. The potential hazards from x-ray machines were generally discounted. Each person using radioactive substances or operating one of the other radiation machines was considered to be a competent, highly-skilled technician. Any needful radiation protection for himself and his associates was left in the hands of the individual scientist. Because of imperfections in the machines, or because of lapses in technique during use of machines or radioactive substances, individuals occasionally were injured seriously or killed by radiation. But, still, radiation control was looked upon as a problem of the individual concerned.

Today, however, sources of ionizing radiation are rapidly becoming more and more widely used. Each atomic reactor produces the radioactive equivalent of hundreds of pounds of radium. Radioactive substances are used in increasing numbers of hospitals, industries, and research establishments. X-ray machines are encountered in tuberculosis surveys, in shoe stores, in physician's offices and in foundries. Potentially, ionizing radiation has come to affect the environment of every member of the community.

Almost every literate person knows that too much exposure to x-rays, gamma rays, or other atomic radiations is injurious. Even in the children's "comic" books, radio programs, and television shows there is glib mention of potent fictional "ray-guns" and of deadly atomic weapons. Since health authorities have responsibility for other phases of environmental and personal health protection, the general public is looking, naturally, to them for health control of ionizing radiations. To meet this new assignment, health personnel must develop competency in radiological health activities.

Radiological Health has been selected as the inclusive term for all public aspects of ionizing radiation. It embraces understanding of the

281974 O—53—2

nature of ionizing radiations, their interactions with living tissues, and the prevention of injury to people through application of public health methods as well as the encouragement of constructive uses of radiation to promote better health. Need for radiation control or uses for radiation and radioactive substances to improve the public health may be found in almost any health program. It is an essential obligation of the modern health officer to be alert to recognize such needs or uses promptly when and where they are met.

A general belief has developed among health workers that they cannot understand the health aspects of atomic energy and ionizing radiation without extensive study of complex physics and chemistry plus a working knowledge of higher mathematics. This is true only if one aspires to become a radiobiologist or a biophysicist. It is not true when the goal is merely practical understanding of radiological health and of the place for radiological health activities in the general health program. For this purpose, one has only to learn about the penetrating powers of ionizing radiations, their harmful effects on living things, and the ways of keeping people and radiations apart.

Classically trained public health people need three major attributes for successful study of radiological health. They are: a scientific curiosity, some knowledge of elementary arithmetic, and a genuine interest in public health.

B. Atomic Physics and Isotope-Produced Radiations

Energy changes inside atoms produce ionizing radiations. These radiations are absorbed by producing physical and chemical changes in other atoms or aggregates of atoms called molecules. Obviously, knowledge about the structure and behavior of atoms, their component particles, and the molecules they compose forms the key to understanding biologic effects of radiations and the need for their public health control.

Modern physicists and chemists know that all matter is made up of atoms. Atoms exist in only a limited number of chemical varieties. Ninety-eight chemically different kinds of atoms (the chemical elements) have been isolated and identified here on earth. Ninety are found in nature. The remaining eight have been made only recently in the laboratory. They are technitium, promethium, neptunium, plutonium, americium, curium, berkelium, and californium.

Atoms are so tiny it would take more than 100 billion billion ($10^{20}$) of them placed side by side to cover one surface of the head of a common

pin. They are obviously too small to be seen and too light to be weighed individually. To simplify comparison of the masses or weights of the several kinds of atoms, scientists use a special unit of measure called the mass unit. Its value was selected many years ago as one-sixteenth the mass of an oxygen atom and currently is taken as $1.7 \times 10^{-24}$ grams.

Physicists have succeeded in exploring the interior of these tiny units. They are satisfied that atoms have a definitely organized internal structure. All of them include two main parts: a nucleus and an electron cloud. Because of their physical and chemical behavior, it is believed that the nucleus is centrally located and is enveloped by the electron cloud which is composed of an orderly moving group of orbital particles. So definite is this concept that it has become customary to think of atoms as miniature solar systems (Diagram A)

For convenience in referring to them, the elements have been tabulated according to the relative electrical charges on their nuclei and assigned numbers from 1 to 98. These numbers are known as the Atomic Numbers (Appendix B) and may be used to designate the different elements. Elements number 99, 100 and above, although there is sound scientific evidence that they should exist, have not yet (1/1/54) been reported.

Atomic nuclei are made up of various combinations of two types of fundamental particles called protons and neutrons. These particles are approximately equal in mass, each weighing about one mass unit. Protons have a unit positive electric charge. They may be represented by the symbols p or ⊕. Neutrons have no electric charge. They may be represented by the symbols n or ○

The orbital particles composing the electron cloud are called electrons. In hydrogen, the simplest of the atoms, the cloud consists of a single electron: in californium, the most complex, it contains ninety-eight. Each has a negative electric charge equal in value to the positive charge of a proton. Electrons weigh only about 1/2000th of a mass unit: in other words, a group of 2,000 electrons would have about the same mass as a single proor neutron. They may be symbolized as $e$ or ⊖. Because of their negative electric charge they are sometimes called negatrons.

DIAGRAM A

Atom of the Element Neon

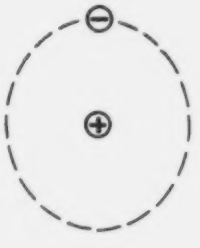
The usual atomic state is one of electric neutrality. The number of orbital electrons equals the number of protons in the nucleus and the net negative and net positive charges balance each other. Each atomic number equals the number of protons or of electrons present in the atoms of its chemical element. Therefore, the atomic numbers also represent the total positive or negative atomic electric charges of the elements. Since the neutrons and protons are the heavy atomic component, most of the mass of an atom lies in its nucleus.

To review for a moment, atoms are made up of three kinds of subatomic particles:

Subatomic Particles

| Name | Electric charge | Mass | | Location |
|---|---|---|---|---|
| | | Grams | Approximate mass units | |
| Electron.... | -1 | $9.1 \times 10^{-28}$ | 1/1860 | Orbits |
| Proton..... | +1 | $1.7 \times 10^{-24}$ | 1 | Nucleus |
| Neutron..... | 0 | $1.7 \times 10^{-24}$ | 1 | Nucleus |

The chemical properties of atoms are determined by the numbers and arrangements of the orbital electrons they contain. Single protons each with one orbital electron form the simplest kind of atoms. They are hydrogen atoms and may be represented by the diagram:



It has become accepted practice to designate the various elements by symbols (Appendix B). The symbol for hydrogen is H.

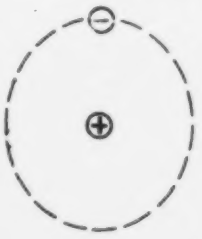
Atoms containing two nuclear protons and, therefore, two orbital electrons form the next atomic configuration. Atoms of this kind are helium. The symbol for helium is He.

Three nuclear protons and three orbital electrons are in the third kind of atom, lithium. The symbol for lithium is Li.

The addition of nuclear protons and peripheral electrons continues step by step up through the ninety-eight elements. Atoms with 92 protons

and 92 electrons are uranium. Neptunium, plutonium, americium, curium, berkelium and californium have 93, 94, 95, 96, 97, and 98 protons and electrons, respectively. Californium, however, does not weigh 98 times as much as hydrogen, it weighs about 250 times as much. Even helium, hydrogen's next door neighbor, weighs about four times as much rather than twice as much as hydrogen, atom for atom. The presence of the neutrons in the atomic nuclei accounts for the weight discrepancies.

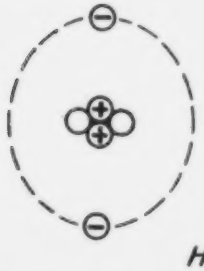
The total weight or mass of an atom expressed in mass units is known as its Mass Number (Appendix B). As was indicated, simple hydrogen is made up of one proton and one electron. Because of its proton, its mass is approximately one unit so its mass number is one. Also, its nuclear charge is one so its atomic number is also one:



Mass Number = 1
Atomic Number = 1

*Hydrogen*

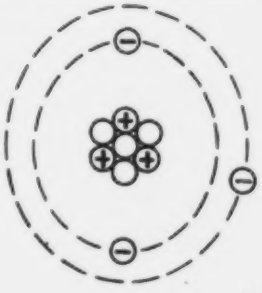
Normal helium is composed of two protons, two neutrons and two orbital electrons. It has the proper electron and proton configuration for atomic number two and mass number four:



Mass Number = 4
Atomic Number = 2

*Helium*

Lithium, element number three in nature, has three protons, four neutrons and three electrons to give it an atomic number of three and a mass number of seven:



Mass Number = 7
Atomic Number = 3

*Lithium*

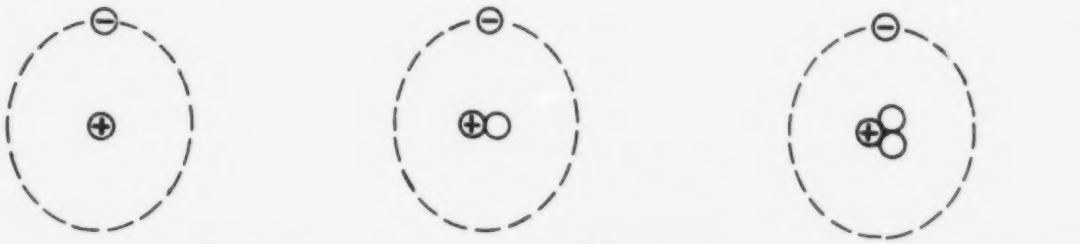
And so on up the atomic scale.

Occurrence of more or fewer neutrons in atomic nuclei has no effect on their chemical properties. These chemical properties depend upon the proton charge or the number and arrangement of the orbital electrons. Therefore, it is possible for the atoms of any given chemical

281974 O—53——3

element, all of which contain identical numbers of protons, to have differing numbers of neutrons. The different species of the element, constructed with different numbers of neutrons, are called isotopes of that element. The existence of isotopes was first shown in the rare gas, neon.

There are three known isotopes of hydrogen:



*Protium* *H-1*

*Deuterium* *H-2*

*Tritium* *H-3*

Each has a single proton and one electron. Each atomic number is one, so all three of the isotopes can only be hydrogen. They differ, however, in having zero, one, and two neutrons in the nucleus and so have mass numbers of one, two and three respectively. Chemically, they behave identically, as chemical behavior is governed by electron configuration. But physically, in properties affected by mass, they differ. These differences appear in the rates of gaseous diffusion, rates of thermal diffusion, behavior in the ultracentrifuge, and in related properties.

Every one of the elements has three or more isotopes (Appendix C). Three isotopes of element number 2, helium, have been isolated: they are helium-3, 4, and 6, containing two protons, two electrons, and one, two, and four neutrons. Carbon has at least five isotopes: carbon-10, 11, 12, 13, and 14; tin has twenty-two isotopes ranging from mass 107 to mass 136.

In atomic physics and physical chemistry, it is often important to indicate both the atomic number and the mass number of an isotope. For this reason, it has become customary to add to the symbol of the element its atomic number as a subscript and the mass number of the particular isotope as a superscript. The three varieties of hydrogen then appear as, ${}_1H^1$, ${}_1H^2$, and ${}_1H^3$: the helium isotopes as ${}_2He^3$, ${}_2He^4$, and ${}_2He^6$: the carbon isotopes are ${}_6C^{10}$, ${}_6C^{11}$, ${}_6C^{12}$, ${}_6C^{13}$, ${}_6C^{14}$; and so on up the scale.

Powerful forces tug at the protons and neutrons in the nuclei of atoms. Some of the forces act to keep the nuclear particles together. This group includes the strong attractive nuclear forces, existing

between nuclear particles. Other of the forces tend to thrust the nuclear components apart. This group includes the electrostatic or coulomb forces between the protons tending to push them away from each other. The two sets of forces maintain a balance in the combinations of protons and neutrons which form the various isotopes of the 99 known elements. The several forces in these nuclei differ in magnitude and the stability of their balance varies from isotope to isotope depending on the total number of particles present and the relative number of each kind. In some of the combinations, the balance is steady and hard to upset. Nuclei of this sort endure and are spoken of as being stable. In other of the combinations, the balance of forces is much more easily upset. Nuclei of this sort will undergo spontaneous rearrangement, ejecting charged particles, to attain more stable combinations of protons and neutrons. These isotopes are unstable; their nuclei are said to undergo radioactive decay; and they are called radioactive isotopes or radioisotopes.

In the lighter elements, such as carbon or oxygen, combinations of approximately equal numbers of neutrons and protons form stable nuclei. Hydrogen-1 and 2 and carbon-12 and 13 are stable. Hydrogen-3 and carbon-10, 11 and 14 are radioactive. As the mass numbers of the successive elements increase, more neutrons than protons are needed to maintain stability. For the elements like platinum, gold and bismuth, the stable ratios of neutrons to protons increase to a value of approximately 1.5. In the very heavy elements, above bismuth-210, all atoms are radioactive regardless of their neutron-proton ratio. This group includes radium, uranium and plutonium.

Each of the elements has at least one known radioisotope. Some like tin and xenon have many stable forms; others like arsenic and aluminum have but one; and still others such as promethium and radium have only radioactive forms. If all the isotopes of all the elements are tabulated according to their mass numbers (Appendix C), it will be seen that there are approximately 1100 known isotopes. Only about 280 of these are stable and the rest, 800 or so, are radioactive.

Nature's recipes for atomic nuclei have been standard for billions of years. Using the machines of modern science it is possible to combine neutrons and protons almost as we wish but, after the combination is made, nature will change it by radioactive decay until the nucleus becomes one of her own liking. Carbon-14, which is man-made, decays to nitrogen-14 by emitting a high speed electron:

$$_{6}C^{14} \longrightarrow {}_{7}N^{14} + {}_{-1}e$$

The nitrogen-14 is stable.

Man-made radioactive isotopes are called artificial radioisotopes. Those found in nature are known as natural radioisotopes. All radioisotopes, whether natural or artificial, decay by emission of alpha, beta, or gamma radiations. Alpha radiations are high-energy, charged particles consisting of two protons and two neutrons. They have a mass of four units and bear two positive electric charges. Upon acquiring two electrons from the environment they become helium atoms. Alpha particles may be symbolized as $\alpha$, or $_2He^4$. Alpha rays are streams of alpha particles.

Beta radiations are energetic particles having a mass and electric charge equal in magnitude to those of an electron. The charge may be either positive or negative. Beta particles may be symbolized as $\beta+$ and $\beta-$ or $_{+1}e$ and $_{-1}e$. Positive beta particles are often called positrons to differentiate them from the negative ones which, when they lose their energy, are normal electrons or negatrons.

Gamma radiations are high energy photons or rays similar to light and radio waves but of much higher frequency. They have no electric charge and may be represented by the symbol $\gamma$.

For convenience in discussing the energies of radiations, of atoms, and of molecules, a special unit, the electron volt, is used. One electron volt (e.v.) is the energy given a single electron as it moves across an electric potential difference of one volt (Diagram B).

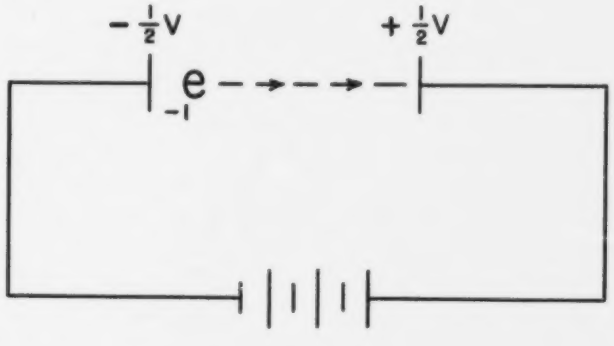



**DIAGRAM B**
**Definition of Electron Volt (e.v.)**

The volt used to define the electron volt is the same unit that is used to measure electricity in everyday life. Ordinary household circuits operate at about 110 or 220 volts and automobile batteries provide approximately six volts.

Since diagnostic x-ray machines operate at a peak voltage of 100,000 volts or 100 kilovolts, the speediest electrons flowing through the tube of one of those machines have energies of about 100 kiloelectron volts (Kev.). Energies of ionizing radiations such as alpha particles or gamma photons can range from a few thousand up into the millions of electron volts. The following examples are helpful in visualizing the amount of energy represented by electron volts:

1) One electron volt is $1.6 \times 10^{-12}$ ergs.

2) One million electron volts (Mev) is enough energy to lift a milligram weight one millionth of a centimeter.

3) The thermal energy of motion of molecules at room temperature is about 1/30th of an electron volt.

4) The energy of the bonds holding atoms together in the molecules of chemical compounds range from fractions of an electron volt up to ten or twelve electron volts.

5) The nuclear binding energy holding the protons and neutrons together in the nuclei of atoms is of the order of millions of electron volts.

(The ratio of molecular binding energy to nuclear binding energy, it may be noted, is commonly on the order of one to one million).

The naturally occurring radioisotopes are frequently alpha emitters, while the artificial or man-made radioactive substances are almost all beta emitters. Any particular radioactive atom is either an alpha emitter or a beta emitter. It cannot emit both kinds of particles simultaneously. However, a single atom can emit both an alpha and a gamma radiation or a beta and a gamma radiation. Radium-226, when it decays, emits an alpha particle of 4.79 Mev energy and a gamma photon of 0.19 Mev energy. In the process, radium-226 changes into radon-222:

$$_{88}Ra^{226} \longrightarrow {}_{86}Rn^{222} + {}_{2}He^{4} + \gamma + \text{Energy}$$

Phosphorus-32 decays into sulfur-32 by emitting a negative beta particle of 1.70 Mev energy:

$$_{15}P^{32} \longrightarrow {}_{16}S^{32} + {}_{-1}e + \text{Energy}$$

Radioactive decay of atoms involves emission of charged particles. It results in increase or decrease of the nuclear electric charge and of the number of orbital electrons, with resulting changes in chemical and physical properties of the atoms. The change is always in the direction of

281974 O—53——4

greater nuclear stability. In some cases, the changed atoms are stable and endure; in others, they also may be unstable and a successive chain of decays may have to take place before a stable pattern is reached.

For any particular atom, decay does not take place gradually. It is an all-or-none reaction. Scientists know of nothing they can do to affect the stability of any given nuclear arrangement. Radioactive decay can neither be slowed nor hurried by any practical means. Among a number of identical radioactive atoms, disintegration events occur strictly at random so prediction of when any specific nucleus will decay is not possible. This very randomness, however, favors statistical analysis of radioactive decay. If large numbers of atoms of the same radioisotope are considered and small bits of matter do contain fantastic numbers of atoms, the number that will disintegrate in any given length of time can be estimated with great accuracy. For radioactive atoms of every kind, the number decaying during a given time is proportional to the number originally present. If the interval chosen is that in which 50 percent of the atoms present will decay, then in each successive identical interval, 50 percent of the remaining radioactive atoms will decay. Time intervals of this sort are called radioactive half-lives ($T\frac{1}{2}$) (Diagram C):

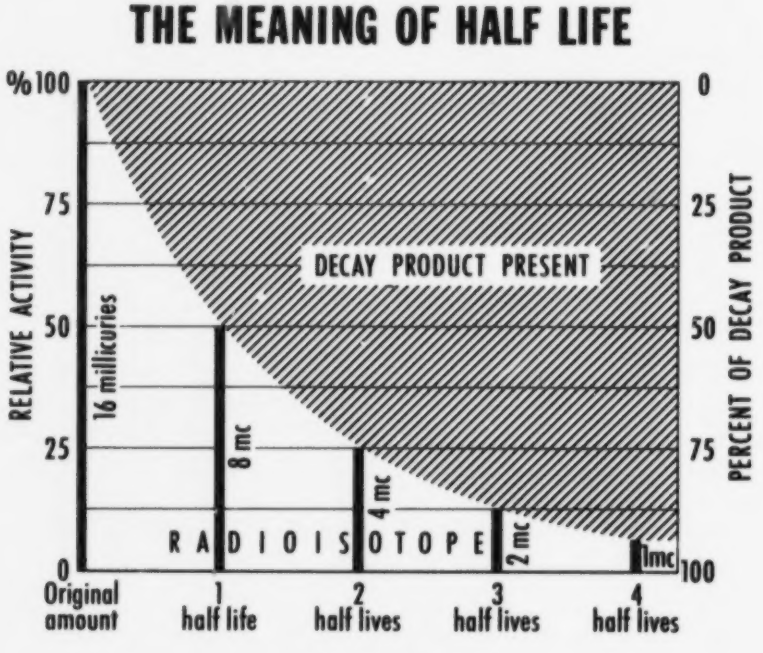



DIAGRAM C

The half-life of each radioisotope has a fixed value. Each radioisotope's decay pattern also, is constant. Only one or two kinds of radiation are emitted at each disintegration. Half-lives and decay patterns are so

characteristic that they can be and are used to help identify the various radioisotopes. Half-lives of the known radioisotopes range from fractions of seconds for some to millions or billions of years for others. (Appendix E). Nitrogen-12 has a half-life of 13/1000th ($1.3 \times 10^{-2}$) of a second. Iodine-131 has a half-life of 8.14 days. Carbon-14 has a half-life of 5580 years. Bismuth-209 has a half-life of about 300 quadrillion ($3 \times 10^{17}$) years. Radioactivity appears to be theoretically possible in a number of isotopes now considered to be stable. It may be in time to come, when they can measure decay more accurately, our scientists will find that still other elements are radioactive with half-lives of quintillions ($10^{18}$) or more years.

From the public health viewpoint, the important fact of radioactivity is that energy release in the form of harmful radiations is an integral part of the process. The health worker is concerned with radioactive substances not because they decay, but because in decaying they emit alpha, beta, and gamma radiations which may affect plants, animals and people.

C. Machine-Produced Radiation

The current surge of public interest in ionizing radiation was stimulated by the development of atomic energy and employment of the atom bomb. As a consequence, there is a tendency to associate radiation with radioisotopes to the exclusion of other sources. Despite this common trend public health people should keep in mind that ionizing radiations can be produced by machines as well as by radioactive substances.

There are many kinds of machines which produce radiations. Fluoroscopes and radiographic machines are used in medicine and industry, primarily because the rays they produce penetrate opaque materials and make their internal structure visible. Some radio transmitters, high voltage rectifiers for changing alternating current to direct current, and high voltage, projection type television receivers* generate x-rays as a by-product of their operation. Cyclotrons, betatrons and similar machines are used to accelerate protons, electrons, or other charged particles and so produce ionizing radiations, usually for experimental purposes.

At the present time, because radiation-producing machines are so

* The picture circuits of ordinary, direct-view television receivers in use today operate on from about 7,500 to 15,000 volts. They present no radiation health hazard as the soft radiations produced within the picture tubes are absorbed by the tubes' thick enveloping glass.

widely used, the hazards of radiation from them probably have more significance for the general public than do the hazards of radiation from radioisotopes. Radiations from machines can be as potent as radiations from radioisotopes. A living tissue bombarded by a given number of beta particles of a specified energy is injured to a given degree regardless of the source of the particles. It does not matter whether the radiation source is a betatron or a beta-emitting radioisotope.

As is the case withionizing radiation produced by radioactive decay, ionizing radiations are produced by machines through excitation of atoms or parts of atoms. Also, they are absorbed by producing energy and chemical changes in other atoms and molecules. These changes are identical with those produced by the ray from isotopes. Once an ionizing radiation has emerged from its source it is no longer possible to determine whether it was produced by a machine or by radioactive decay. X-rays, gamma rays, and ionizing particles detected in passage bear no markings to indicate whether they were made by man or by nature.

Machines produce x-rays by bombarding a metal or other dense target with a stream of high-speed electrons. The rays result when the electrons suddenly lose speed in the intense electric fields surrounding the target atoms. The production of x-rays by machines is carried out in large vacuum tubes somewhat similar to ordinary radio tubes (Diagram D).

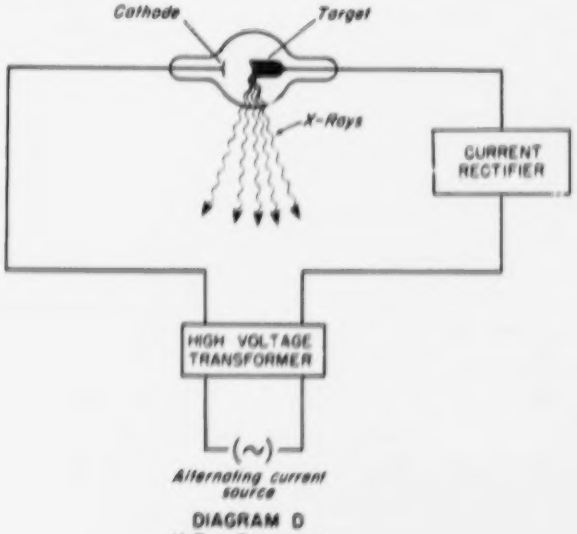



DIAGRAM D
X-Ray Generator

The two major electrodes are fixed at opposite ends of the tube, within the vacuum. One electrode is the cathode. The other is the anode or target. High voltage enables an electric current to leap the gap between the electrodes. When this current which is made up of electrons, strikes the

target, a part of the energy is converted into x-rays that pass out through the walls of the vacuum tube much as light passes out of an electric light bulb.

X-rays emerge in all directions from the target. It is customary to use only a small beam of x-rays that can be directed where it is needed. For this reason, in modern equipment, the tube is enclosed by a shielding layer of lead or other dense material, leaving only a small opening through which the useful beam may pass. The higher the voltage of the electric current used to activate the tube, the more penetrating the resulting rays will be. Therefore, x-ray tubes use high voltages, from 50 thousand to more than 10 million volts.

Literally thousands of x-ray machines and fluoroscopes are in daily use throughout the country. Medical and dental x-ray machines and shoe-fitting and industrial x-ray machines provide a relatively large potential radiation exposure for considerable numbers of the population. The radiations from these machines affect x-ray technicians and physicians, dentists and industrial workers, nurses, and the general public.

Particle accelerators are, for the most part, research machines. They concern only a few thousand people at present. Health officials need to know of particle accelerators in their communities, but, currently, few radiological health problems result from operation of these machines.

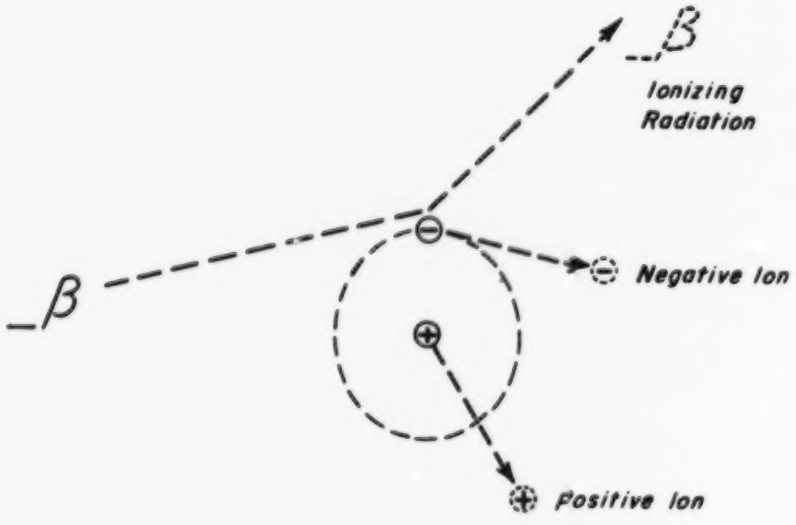
Machine-produced radiations can be used constructively when their injury potential is understood and controlled. Modern physicians and industrialists use these radiations for examinations, inspections, and process controls that are otherwise difficult if not impossible. For economic reasons alone, radiation machines are going to increase in common use. Because of the widespread use of these machines, the health importance of their radiations should be fully recognized by the persons responsible for them as well as by health authorities. If the hazards of these machines are understood, we can learn to live with them safely.

D. Absorption of Ionizing Radiation

In planning radiological health activities, it is useful to know how ionizing radiations are produced and how they interact with matter. But, for a practical understanding of the import of radiations to public health, it is a necessity to have a working knowledge of the process and results of the absorption of ionizing radiations by human tissue.

Ionizing radiations, whether they arise from radioactive decay, from radiation-producing machines, or from cosmic sources, share one distinc-

tive property. Whatever their source, during the process of absorption, all types interact with matter by splitting atoms and molecules into pairs of electrically charged fragments called ions (Diagram E).




## DIAGRAM E

### Ionization of an Hydrogen Atom by a Beta Particle

It is because of this power to create ions that these radiations are known as "ionizing." Ionization can occur in any kind of matter. Ionization of living matter results in tissue changes that may affect health. The degree of tissue ionization produced depends upon the composition of the tissue and the quantity, type, and energy of the radiation.

Most particulate radiations, such as alpha and beta radiations, are completely absorbed or stopped by relatively thin layers of matter.

In contrast, gamma- and x-rays are only attenuated by passing through matter. Successive layers of identical material and thickness reduce these radiations by the same ratio. If a given thickness of lead reduces a given x-ray beam to one half its original intensity (Diagram F) a similar one twice as thick will reduce it to one half of one half or one quarter of its original intensity, and one three times as thick will reduce it to one half of one half of one half or one eighth of its original intensity. It would take seven such half layers to reduce an x- or gamma-ray beam to one 1/128th or a bit less than one percent of its original strength. Radiation absorption

of this kind is called exponential absorption as it may be expressed by an exponential mathematical equation. Any intensity of x- or gamma radiation can be reduced to any desired level if a sufficient thickness of absorbing material is used.

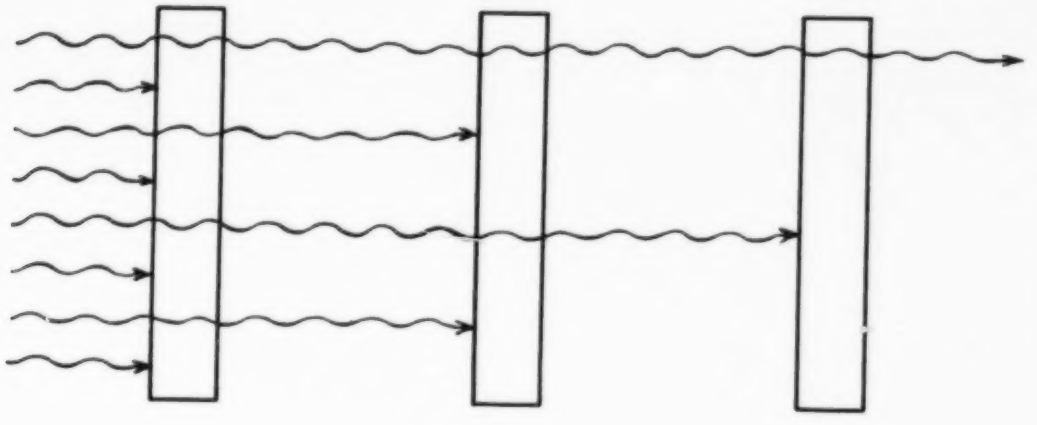


DIAGRAM F

**Exponential Absorption of X-Ray and Gamma-Rays**

Although all of the ionizing radiations produce ions as they are absorbed, their ionization patterns differ significantly. These variations are important in determining whether the radiation is biologically potent from outside the body (external radiation) or whether, to affect the tissues, the source of the radiation must be located within the body itself (internal radiation.)

The measure commonly used in comparing ionizing powers of the several ionizing radiations is called their "specific ionization". Its value is stated as the average number of ionizations or ion pairs formed by an ionizing particle or photon per centimeter of path length in air. This number depends upon the charge, and speed of the particle or the energy of the photon.

Alpha particles have large specific ionization values. Since they create many ions per unit of path length, they dissipate their energy rapidly and penetrate only short distances. Alpha particles are normally a hazard to health only in the form of internal radiation.

X-rays and gamma rays have quite low specific ionization values. They ionize sparsely over long paths and are quite penetrative. As a group,

these radiations constitute the chief health hazard of external radiation, although gamma-rays can be a hazard also as internal radiation.

Beta particles are light in weight and carry single negative charges. Their specific ionization values are intermediate between those of alpha particles and gamma- and x-rays. They ionize matter somewhat sparsely, dissipate their energies relatively quickly, and are moderately penetrative. Beta particles can be a health hazard either as internal or external radiation.

Radiation absorption and the ionization resulting from it has three aspects significant to public health. First, the production of ions within their tissues can injure people, animals, and plants. Second, exposure to ionizing radiation can be controlled by use of radiation shields of lead, concrete, and other substances. Third, in practice, radiation is detected and measured through the ions created by its absorption.

## Part II: Biologic Effects of Radiation Absorption

### A. How Radiation Initiates Changes in Living Tissue

When ionizing radiations are absorbed by matter, both the radiations and the absorbing substance are changed. The radiations lose a part or all of their energy, and the matter is ionized. If the absorber is living tissue, the ionization produced in it can have significant and sometimes deadly effects.

Most well-informed people today know or have heard that too much exposure to atomic radiations can maim or kill. The fact that injury or death may follow excessive exposure to any of the ionizing radiations has been demonstrated repeatedly by experiments on animals and by medical case histories.

In passing, it should be noted that, in addition to the ionizing radiations, other more familiar radiations such as heat and light under certain circumstances should be classed as harmful. Exposure to excessive heat, even flash exposure to sufficiently intense sources, may result in severe or fatal burns. Exposure to direct sunlight for too long a period may produce painful sunburn, or (at a chronic level of exposure) skin cancer. Because both heat and light are familiar, their potential threat to health is accepted as a matter of course. Yet, the biologic actions of even these "well-known" radiations are not completely understood.

Injuries from heat and light tend to be surface injuries because these radiations are absorbed by relatively thin layers of tissue. Injuries from ionizing radiations may be superficial, deep, or both depending on the type, the quality, and the penetration of the particular radiation in question.

Gamma and x-ray photons, by their nature, are non-material; and alpha and beta particles are far too tiny for the human body to detect. Even large amounts of these radiations cannot be seen or felt. Moreover, the injuries they produce are seldom immediately apparent. For these reasons, few people are prepared psychologically to pay more than lip service to the existence of a health hazard from radiation whose presence they cannot even sense.

There is no reason why radiation effects should not be understandable in terms of molecular or atomic levels of action. Bacteriology has taught, for years, that the body combats infectious diseases at the cellular level with white blood cells pitted against bacteria. And immunology teaches that anti-bodies (which are protein molecules) neutralize bacterial antigens (which also are protein molecules). These actions are as imperceptible to

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the senses as are the actions of radiation, yet they are accepted because their rules of behavior are understood. Similarly, mastery of the rules of radiation should provide a parallel understanding and acceptance.

The remarkable effectiveness of ionizing radiations in causing biologic injury stems from their property of acting directly on the individual atoms and molecules composing tissue. Radiations may eject electrons from atoms, break up chemical compounds, displace atoms in organized molecules and, in general, cause quite important changes in the submicroscopic structure of cells.

The biologic potency of radiations may perhaps be appreciated more concretely if one compares, for example, the relative power of alpha particles to ionize and injure living molecules (Diagram G) to the power of shotgun pellets to injure people (Diagram H).

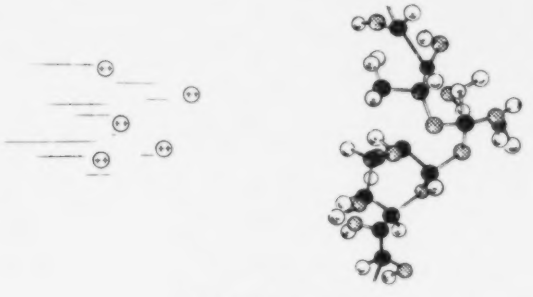


DIAGRAM G
Alpha Particles Bombarding a Molecule

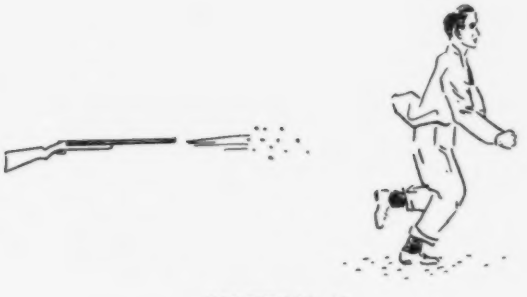


DIAGRAM H
Shotgun Pellets Fired at a Man

Relative to their respective targets, alpha particles are 28 times heavier than #5 shot (see Appendix D). And the speed of 1 Mev alpha

particles exceeds the muzzle velocity of #5 shot from a 12 gauge shotgun by well over a quarter of a million times. A shotgun fired at a man can injure or kill him. Alpha particles striking tissue can ionize its molecules and injure or kill its cells. A single shotgun pellet, if it strikes a vital spot, can be fatal. A single alpha particle if it ionizes a critical molecule can kill a cell or possibly start a cancer.

Knowledge of how ionizing radiations cause injury to tissue is incomplete. Most scientists agree that the first event to occur is absorption in the exposed tissue of energy from the radiations. The absorbed energy ionizes atoms and molecules composing the tissue. Exactly what takes place between these ionizations and the emergence of the biologic effect is not known. Many theories about the probable sequence have been suggested. The theories differ in specific details but most of them seem to be based on a standard idea: that tissue damage probably stems from ionization of atoms in or near living cells with a consequent rupture of the molecules containing these ionized atoms.

However the biologic changes are produced, agreement seems general that exposure to atomic radiations is basically harmful to body tissues. The specific injury produced by radiation in any given circumstance probably depends on many variable factors such as the density of ionization, the kind of tissue irradiated, and the kind or location of the molecules affected. Observed injuries include the mutation of genes, inactivation of enzymes, inhibition of cell division, and fatal disturbance of tissue functions.

B. Units of Radiation and Radioactivity

Radiological health workers commonly use three standard units of radiation and radioactivity. These units are the roentgen, the roentgen equivalent physical, and the curie. The roentgen and roentgen equivalent physical are used to express radiation dosage. The curie expresses the quantity of material present in terms of its radioactivity.

Standard definitions of the units are included in the glossary (Appendix A). They are not repeated here as these definitions are of use primarily to physics students and research scientists. Health workers interested in radiological health must know about the definitions and where to find them, but they may not find it necessary to be familiar with the refined details of the definitions.

Instead, if these health workers develop a working concept of how much radiation each unit represents in terms of its biologic effects, radiation doses expressed in these units will take on practical meaning. Health workers can develop this working concept most readily through frequent

use of the units in measuring doses of radiation, much as the everyday calculation of time and distance has developed concrete associations for the more familiar measures such as a second, an hour, an inch, a mile.

The roentgen (r) by definition measures absorption of gamma and x-rays only. It was named in honor of Wilhelm Roentgen who made the first practical use of x-rays more than 50 years ago.

The roentgen unit is applied to both gamma radiations and x-radiations because, except for the sites of their origin in the atom, these two radiations are basically identical. X-rays are most familiar as the radiation produced by medical and industrial x-ray machines; gamma rays as one of the radiations from radioactive substances.

Although the roentgen actually is an expression of the ability of gamma radiations and x-radiations to ionize air, it has come to be used also as a measure of radiation dosage to human beings.

As one roentgen is an appreciable biologic dose of ionizing radiation, for medical-biological purposes a subunit, the milliroentgen (mr) or 1 thousandth (1/1000) of a roentgen, has been recognized. The International Committee on Radiation Protection recommends that every effort be made to reduce exposure to all types of ionizing radiations to the lowest possible level, and that it certainly not exceed 0.3 roentgen or 300 milliroentgens per week. The exposure required to take one 14" x 17" medical x-ray picture of a person's chest is about 0.05 roentgen or 50 milliroentgens. A whole body exposure of about 450 roentgens, according to authorities on radiation effects, will kill 50 percent of persons so exposed. In man, a whole body exposure of about 100 roentgens is expected to produce 10% radiation sickness.

Because the roentgen applies only to gamma rays and x-rays, there is need for an additional unit to express dosage of the other kinds of ionizing radiation. The roentgen equivalent physical (rep) is used for this purpose For our purposes, it may be said that one roentgen equivalent physical is the amount of beta, alpha or other particulate ionizing radiation whose absorption imparts to tissue the same amount of energy as does the absorption of the roentgen of gamma or x-radiation. Roentgens equivalent physical are computed rather than measured.

In practical usage, for radiological and other health purposes, mixed radiation (e.g. beta-gamma) and particulate (e.g. beta) radiation fields are sometimes measured with gamma-standardized measuring instruments. The readings so obtained may be recorded, as a matter of expediency, in "roentgens." When such approximations of dosage are made, the need for proper evaluation of their meaning must be kept in mind.

For measuring amounts of a radioactive substance, it has become customary to use the rate of its radioactive disintegration rather than the effects of the radiation it produces or the radiation itself. This is necessary because some radioactive substances emit more than a single radiation with each disintegration.

The curie (c) is the accepted unit of radioactive disintegration. It was named in honor of the Curies for their pioneer work with uranium, radium, and polonium. One curie, biologically speaking, is a very large amount of radioactivity. For practical purposes, a gram of pure radium is one curie of radium. Two smaller units or subunits, the millicurie, 1/1000th curie, (mc), and the microcurie, 1/1,000,000th curie, (uc), are frequently used to measure biologically significant amounts of radioactive substances.

One tenth of a microcurie, (0.1 uc), of radium fixed in a human being's body is considered to be the maximum amount that within a lifetime will produce no noticeable deleterious effects. The threshold amount of radium fixed in the tissues for production of the most serious effects, anemia and damage to bone, appears to be of the order of one microcurie (1 uc).

C. Biological Effects of Radiation

The first practical use of ionizing radiation was Wilhelm Roentgen's picturing of the bones of the hand and arm by x-rays in 1895. At that time, no one knew what ionizing radiations might do to living bodies but one effect was soon evident. By the latter part of January, 1896, Mr. E. H. Grubbe, an experimenter and manufacturer of x-ray tubes, reported a reddening or erythema of the skin of his hands from their exposure to x-rays during his study of the fluorescence of chemical compounds. This is believed to be the first recorded instance of injury caused by ionizing radiations.

Within a few years, physiologists reported that radiation produced changes in the blood forming organs and the reproductive tissues. By the early 1920's, with a number of industrial and medical uses for radiation developing, scientists had recognized that too much radiation exposure may cause a full spectrum of acute, delayed, and chronic ills, such as tissue necrosis, anemia, decreased vitality, atrophy, and cancer. It is now definite that the wide variety of observed biologic responses to radiation all stem from injury of the individual cells composing tissues. The signs or symptons of the injury may vary depending on the tissue injured, the amount of injury done, and the repair processes involved. Some effects of radiation, such as the killing of a cancer or the "stimulation" of

tissues, benefit the body as a whole. This benefit, however, is a by-product of primary injury to exposed cells. It may result from killing of radiosensitive cancer cells or it may arise from tissue repair processes stimulated by deliberate radiation injury.

So far as we know, there are four possible results of exposing a living cell to radiation. The cell may be killed outright. It may be crippled, either permanently or transiently. Or it may merely have non-essential molecules ionized and, therefore, actually not be harmed at all by the radiation. (See Diagram I.) Symptons of radiation injury (skin erythema, radiation sickness, decreased fertility) appear in an individual only after a sufficient number of his cells have been injured or killed. Unless the exposure has been sufficient to cause skin erythema, there may be no immediate external warning that a sublethal or even a minimum lethal dose of radiation has been received. Some changes appear early. Others may be seen only after prolonged latent periods. Evidence of injury from minimal doses of radiation may not show up for months or even years.

Radiation Kills Some Cells, Injures Others, Spares Most

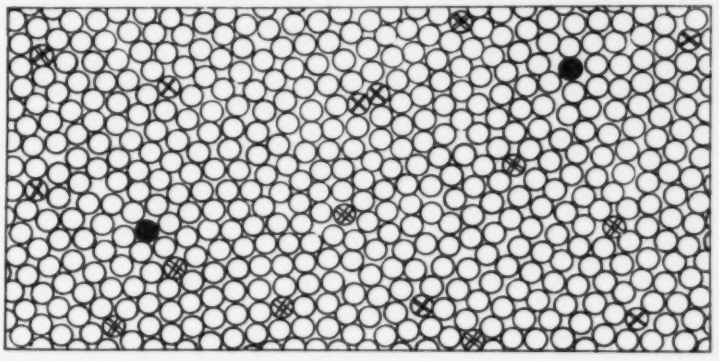


Diagram of Irradiated Tissue

Dead Cell ●
Crippled Cell
Permanent Injury ⊗
Transient Injury ⊗
No Injury ○

DIAGRAM I

The recognizable changes produced in cells by radiation are of many sorts. They include changes in permeability of the cell membrane, changes in the staining characteristics of cells, changes in viscosity of the protoplasm, changes in chromosomes, swelling of cellular components, production of abnormal cell divisions, distortion of cell structure, and many more obscure but measurable changes.

Each of the human body's many different tissues responds differently to radiation exposure. The responses, in general, are a summation of the responses of the various cells and cell types composing the specific tissue.

Rapidly growing or metabolizing tissues are usually more sensitive to radiation than are quiescent tissues. Lymphocytic tissues (lymph, nodes, tonsils) are more easily affected than are muscle or nerve tissues. Tissue cells in an organ are more easily injured by radiation than tissue cells grown in a culture.

Tissues so differ in reaction to radiation absorption that it is possible to classify them, in a loose fashion, according to the doses of radiation they will successfully withstand. Any such classification is empiric and, since it disregards important variables other than dosage, is far from exact. Various authors place some of the tissues in a slightly different order of radiosensitivity. However, the principle of specific tissue sensitivity is generally accepted. The following list* is based on the available data and represents the approximate response of tissues exposed to divided doses of roentgen rays generated at 200 kilovolts.

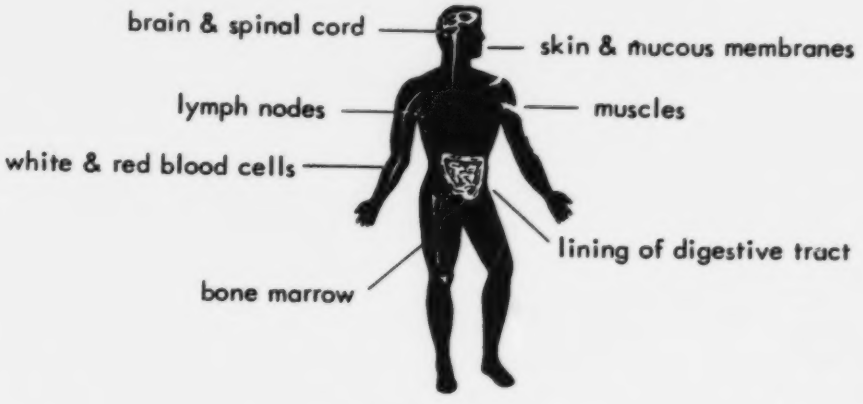



DIAGRAM J
Radiosensitive Body Tissues

* Adapted from Dunlap, Charles E., "Medicolegal Aspects of Injuries from Exposure to Roentgen Rays and Radioactive Substances," Occupational Medicine 1:273 - 301.

A. Highly radiosensitive (cells seriously injured or killed by doses of 600 r or less)(Refer to Diagram J).

Lymphocytes
Bone marrow cells
Sexual cells (testicle and ovary)

B. Moderately radiosensitive (cells seriously injured or killed by doses of 600 r to 3,000 r)

Salivary glands
Epithelium of skin
Endothelium lining blood vessels
Bone (growing)
Epithelium of stomach and intestine
Connective tissue
Elastic tissue

C. Radioresistant (cells show little damage unless dose exceeds 3,000 r)

Kidney
Liver
Thyroid, pancreas, pituitary, adrenal and parathyroid glands
Bone (mature)
Cartilage
Muscle
Brain and other nervous tissue

Tissues injured by radiation show changes in their individual cells, in the blood vessels supplying them, and in their intercellular material. Changes in the blood vessels play a most important part in the total tissue response. In moderately severe radiation injury, these changes appear early. They range from simple thrombosis (clotting of blood within the vessel) to swelling and overgrowth of the membrane lining the vessel. In the more chronic stages, the blood vessels become narrow, tortuous, and partly or completely blocked. Such changes progress over the years. Tissue changes caused by the resulting decrease in blood supply may be profound. Alteration of the material normally found between the tissue cells may vary from slight visible changes to necrosis. Connective tissue fibers separate, swell, and degenerate.

The recovery of tissues showing any specific radiation effect is dependent upon the ability of the individual cells composing it to recover and reproduce. This in turn depends upon the dose of radiation absorbed and the types of cells present. The blood forming organs, the skin, the

membranes lining body cavities, and the secreting glands may regenerate completely and resume their normal functions. Muscle, brain, and portions of the kidney and eye cannot regenerate; repair of them results only in scar formation. Even those tissues that can regenerate may fail to respond after repeated ionization and so cause conditions such as non-healing ulcers or aplastic anemia. Also, repeated regeneration may produce cancerous conditions: epitheliomata, fibrosarcomata, or leukemia. These changes have all been observed in animals following radiation exposures at levels corresponding to doses only slightly above the accepted safe limits for man. (see Diagrams K & L). <u>There are no constant clinical symptoms which can be relied upon to warn of latent radiation injury before the late changes become manifest.</u>

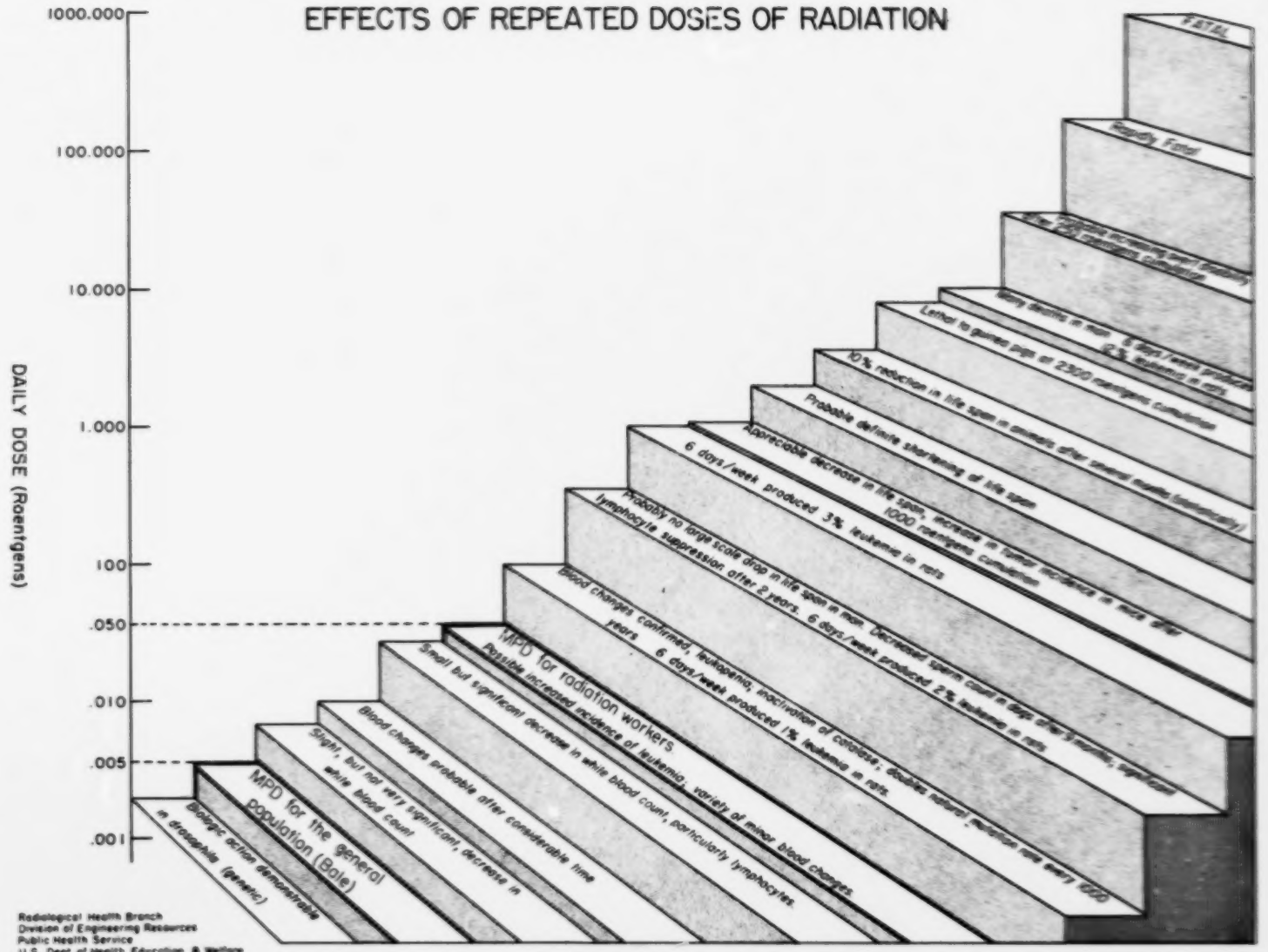

EFFECTS OF REPEATED DOSES OF RADIATION
DAILY DOSE (Roentgens)
1000.000
100.000
10.000
1.000
100
.050
.010
.005
.001
FETAL
Rapidly Fatal
Lethal to guinea pigs at 2500 roentgens cumulative
10% reduction in life span in animals after skeletal maturity (biologically)
Probable definite shortening of life span
Appreciable decrease in life span, increase in tumor incidence in rats after 1000 roentgens cumulative
6 days/week produced 3% leukemia in rats
Probably no large scale drop in life span in man. Decreased sperm count in dogs after 3 months; significant lymphocyte suppression after 2 years. 6 days/week produced 2% leukemia in rats
Blood changes confirmed, leukopenia, inactivation of catalase; doubles natural mutation rate every 1000 years 6 days/week produced 1% leukemia in rats
MPD for radiation workers
Possible increased incidence of leukemia, variety of minor blood changes
Small but significant decrease in white blood count, particularly lymphocytes
Blood changes probable after considerable time
Slight, but not very significant, decrease in white blood count
MPD for the general population (Bale)
Biologic action demonstrable in drosophila (genetic)
Radiological Health Branch
Division of Engineering Resources
Public Health Service
U S Dept of Health, Education, & Welfare
April, 1953

DIAGRAM K

It should be noted that none of the known cellular or tissue responses are completely specific for ionizing radiations. A part or all of them have been seen as a result of other stimuli. Exposure to ultraviolet light from the sun or a mercury arc lamp will burn the skin and, if repeated excessively, can produce skin cancer. Excessive exposure to wet or dry heat can cook or coagulate living tissue. The lipoid vehicles of injected drugs such as penicillin in oil or beeswax may produce abnormal cell mitoses. Changes in oxygen tension may alter membrane permeability. However, a combination of findings such as giant and irregular nuclei plus thick, abnormal connective tissue, plus thick-walled, distorted blood vessels in an area of chronic tissue atrophy is strong presumptive evidence of radiation injury.

Not only is there marked variation in radiation sensitivity of different kinds of cells and tissues within an individual; there is also some variation in the radiosensitivity of individuals of the same species and even more variation among different species.

If killing power is selected to measure the effect of radiation exposure and if mice are selected as the test animals, it may be demonstrated that as the dose of x-rays given over the entire body increases from 200 r to 1000 r the acute mortality rate from irradiation in succesive groups of exposed mice will increase from 10 percent to 100 percent. In addition, the onset of lethal effect will show a latent period which shortens from 8 days to 2 days or less as the radiation dose is increased.

If the dose of radiation that within 30 days will kill 50 percent of individuals exposed (mean lethal dose or LD-50) is selected as a measure of the biologic effect of radiation, the variation in radiosensitivity from animal species to animal species becomes apparent. The approximate LD-50 x-ray doses for several of the more common experimental animals and the estimated mean lethal dose for man are as follows:

| Animal | Dose (roentgens) |
|---|---|
| Guinea Pig | 175 - 250 |
| Dog | 325 |
| Goat | 350 |
| Man | 400 - 450 |
| Mouse | 530 |
| Rabbit | 800 |
| Rat | 825 - 900 |
| Weevils | 1000 - 2000 |
| Molds | 2000 |
| Bacteria (non-spore forming) | 1500 - 2000 |
| Bacteria (spore forming) | 20000 - 50000 |
| Viruses | 50000 - 1000000 |

Table I

LD-50 of x-ray Selected Animal Species

The doses for the animal species have been taken from the literature describing actual experiments on animals. The lethal dose for man is based on animal experiments, on reactions of x-ray therapy patients, and on data collected in Japan.

The potency of radiation to injure tissue is possibly better appreciated when one realizes that one (1) roentgen produces about 1000 ionizations in every body cell exposed. Since the adult human body is composed of about 140 trillion (140,000,000,000,000) cells, this means that exposure of the whole body to the maximum permissible dose for radiation workers (0.05 roentgen/day) will result in about 7 quadrillion ionizations per day in the body. The human LD-50 dose (450 r) will ionize about one atom in every hundred million (100,000,000) in the body or 450 thousand atoms per cell, on the average.

Experimental observations of many different species indicate that radiations induce an aging and debilitating effect. Each roentgen of exposure probably shortens the life-span of an animal by about one ten thousandth (1/10,000). This implies that an exposure rate of 0.4 milli-roentgen equivalents physical (about what man receives from cosmic and other naturally-occurring radiation) may shorten the expected life-span of a human being by about four (4) weeks, if this effect of radiation in man is like that in animals. Also radiation exposure induces an increased susceptibility to infection.

It should be noted that there is a wide range of specific radiation effects from a wide range of doses. In general, the larger the dose, the more prompt and dramatic are its biological effects; the smaller the dose, the more delayed and more insidious are its biological effects. Small, repeated doses of radiation are the most insidious of all. It is this kind of radiation exposure that probably constitutes the major problem of radiological public health.

In every discussion of the effects of ionizing radiations one of the first questions put to the physician is, "Will it make me sterile?" In response, the physician usually finds it necessary to distinguish between potency and fertility. No direct effects on potency have been reported. Fertility has been affected.

Permanent sterilization of the human female requires 400 to 600 roentgens delivered to the ovary. Sterilization of the human male can be produced by 800 to 1000 roentgens in the testis. Either of these doses given as whole body radiation would probably be lethal to the individual and so danger of causing permanent sterilization by single whole body exposures becomes a theoretical rather than a practical question. Reduced fertility and temporary sterility have been induced in human beings by single exposures of 200 to 300 roentgens to the gonads and in animals by repeated exposures of as little as one roentgen per day for a number of weeks.

A survey of radiologists (Hickey & Hall, 1947) reported that the average number of children born to the group surveyed was 1.7, while the average number of children born to a comparable group of physicians not engaged in roentgenology was 3. Inasmuch as the major difference between the two groups of physicians, so far as could be determined, was the practice of roentgenology, these data may indicate a reduction in human fertility from repeated exposure to relatively small doses of x-rays.

Genetic or hereditary changes may arise from doses of radiation much smaller than those needed to affect fertility. Many genetic experts believe that any amount of ionizing radiations may produce hereditary changes cumulative throughout the life-time of the germ plasm line that can and will appear in future generations. There is, however, no current evidence that radiation workers (x-ray technicians, radiologists, atomic workers) who have not abused the maximum permissible dose limits have produced offspring differing from those of the general populace.

Specifically, from the human genetic studies being made of the completed pregnancies among the surviving victims of the atom bombings at Hiroshima and Nagasaki, at least one positive finding has been reported.

The expected normal 1 to 1 male-female ratio among offspring of women exposed within 2000 meters of ground zero (the point immediately beneath the exploding bomb) has been upset by a statistically significant lowering of male births (AEC Semi-annual Report #11).

Ionizing radiation can alter the genes in the body (somatic) cells and in the reproductive (sexual) cells and so cause them to grow or reproduce abnormally. If a gene change occurs in a sexual cell, a mutation will occur in later generations provided that the cell is used in reproduction. If a gene change occurs in a cell of growing or regenerating somatic tissue like skin, liver, bone or bone marrow, it may cause cancerous or other harmful changes in the exposed individual, himself.

Both somatic and sexual cell mutations produced by radiation have been observed in human beings. Statistically significant increases in numbers of mutations have occurred in offspring of parents with a history of exposure to either acute or chronic radiation. An increased incidence of cancers has been recorded in people exposed to amounts of radiation similar to those that produce genetic mutations or cancers in animals. Peller and Pick in 1952 reported that, among physicians in the United States, there were eight to nine times as many fatal leukemias (cancer of the white blood cells) among radiologist-physicians as among non-radiologist-physicians.

The probability that a cell may be ionized increases in proportion to the number of cells exposed to radiation. As there are many more somatic cells than sexual cells in the human body, somatic cells are the more likely to be changed genetically from a given whole body exposure. Thus, from the point of view of radiation-produced gene changes and their effects on human beings, one probably should avoid needless radiation exposure at least as much for his own health protection as for the genetic protection of his progeny.

D. Some Radiological Health Implications*

The nature of radiation injury is such that complete recovery of tissues might be expected only with the elimination and replacement of the cells that have been ionized and permanently crippled. To the extent that these cells persist, it is advisable to regard the effects of radiation as permanent, cumulative, and progressive. Scientists are seeking possible protective substances for internal use to increase resistance to radiation

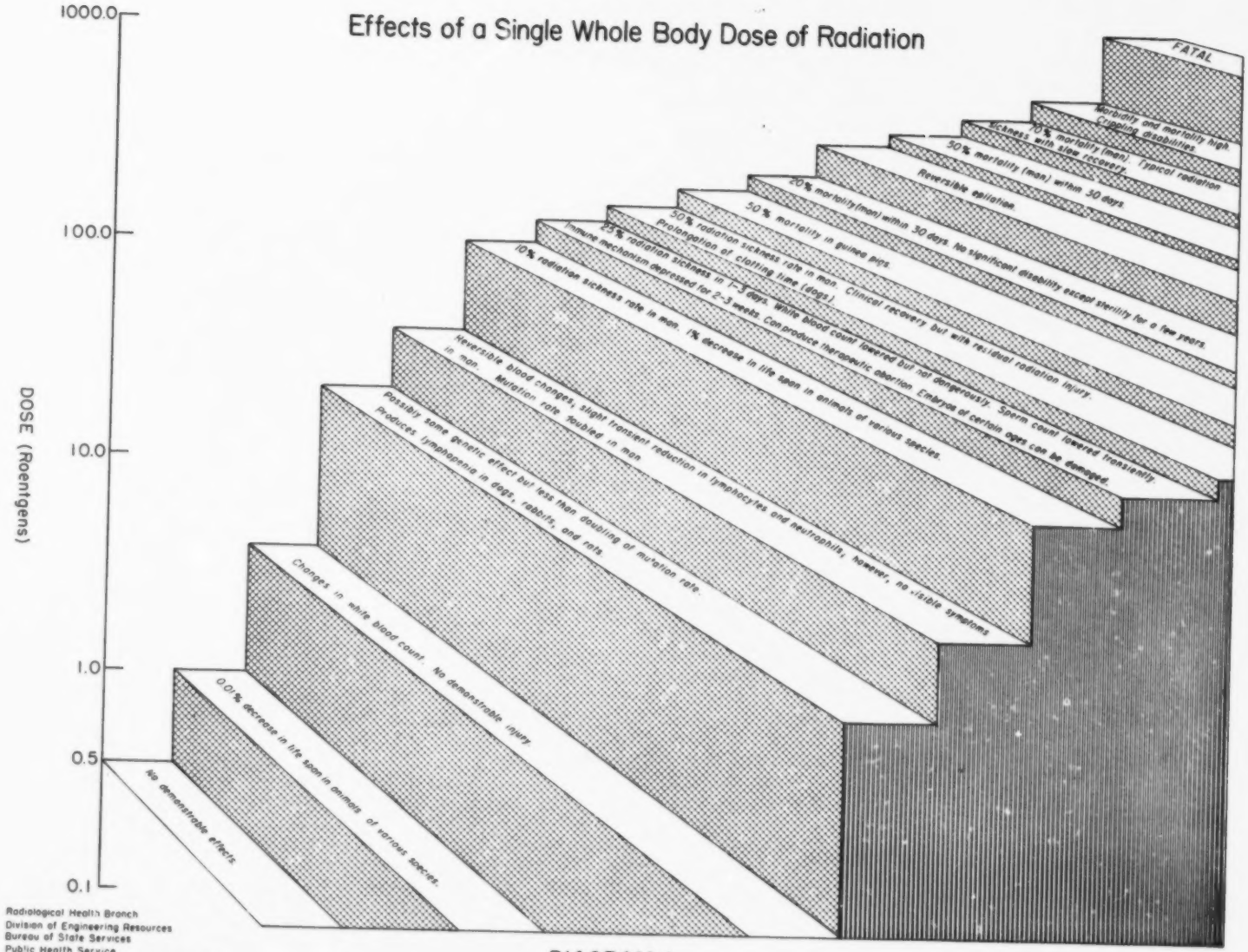
* For specific data on Radiological Civil Defense and the symptons of acute radiation sickness see "Effects of Atomic Weapons" and "Health Services and Special Weapons Defense" (Superintendent of Documents, Washington 25, D. C., Prices: $1.25 and $.60 respectively).

or to promote recovery from radiation injury. To date, no specific treatment of significance outside the field of research has been reported.

Popular, and often professional, interest in the health effects of radiation usually reflects curiosity or concern over the dramatic radiation symptoms: nausea, vomiting, bleeding, anemia and leukemia. A public health program is more properly concerned with the less conspicuous sequellae of repeated, small exposures: debility, loss of vigor, increased susceptibility to illness, retardation of recovery from injury or illness, and other impairments to health that decrease earning power or increase need for community care. Such chronic conditions may subtly affect an entire segment of the population in years to come unless public agencies require adequate protection against radiations (Diagrams K & L).

Quite as serious as the physical problem of radiation control is the problem of the public's psychological reaction to the use of radiation. Misunderstanding of radiation coupled with fear of the unknown are usually enough to make a public wary of the use of atomic radiations except in the healing arts. An injudicious warning about radiation may needlessly increase the difficulty of applying the beneficial uses of radiation such as industrial process controls and, in the future, atomic power. On the other hand, it may be even a worse mistake to pay no heed to the hazards. Public health workers can meet this issue by viewing radiation in proper perspective so as to establish and maintain measures for protection without doing psychological damage by their attitudes and statements.

Once exposure has occurred, little can be done about the injury. It does not improve the situation to alarm or depress those who have been injured. It is the responsibility of the personal physician to explain to the patients, as necessary, how to deal with the consequences of injury. At the same time, it is clear that the occurrence of injury calls for decisive measures to avert a repetition of such injury. In that situation, the person to "be alarmed" is the one responsible for installing protective measures, not the ones who have been injured.


Effects of a Single Whole Body Dose of Radiation
1000.0
100.0
10.0
1.0
0.5
0.1
DOSE (Roentgens)
FATAL
Morbidity and mortality high. Crippling disabilities.
Sickness with slow recovery.
10% mortality (man). Typical radiation
50% mortality (man) within 30 days.
Reversible epilation.
20% mortality(man) within 30 days. No significant disability except sterility for a few years
50% mortality in guinea pigs.
50% radiation sickness rate in man. Clinical recovery but with residual radiation injury.
Protongation of clotting time (dogs)
25% radiation sickness in 1–3 days. White blood count lowered but not dangerously. Sperm count lowered transiently
Immune mechanism depressed for 2–3 weeks. Can produce therapeutic abortion. Embryos at certain ages can be damaged.
10% radiation sickness rate in man. (% decrease in life span in animals of various species.
Reversible blood changes, slight transient reduction in lymphocytes and neutrophils, however, no visible symptoms in man.
Mutation rate doubled in man.
Possibly some genetic effect but less than doubling of mutation rate.
Produces lymphopenia in dogs, rabbits, and rats.
Changes in white blood count. No demonstrable injury.
0.01% decrease in life span in animals of various species.
No demonstrable effects.

Radiological Health Branch
Division of Engineering Resources
Bureau of State Services
Public Health Service
U.S. Dept. of Health, Education, and Welfare
April, 1953

DIAGRAM L

## Appendix A. Glossary of Radiation and Biological Terms

Absorption: Transformation of radiant energy into other forms of energy when passing through a material substance.

Alpha Particles: Charged particles emitted from the nuclei of some atoms and having a mass of 4 units and 2 unit positive electrical charges. They are composed of 2 neutrons and 2 protons. Symbols are $\alpha$, , $_2He^4$.

Alpha Ray: Stream of fast-moving alpha particles; a strongly ionizing and weakly penetrating radiation.

Aplastic Anemia: Anemia or reduction of Red Blood Cell numbers because of lack of their replacement by the bone marrow.

Atoms: The chemical units of which all matter is made. The atom may be defined as the smallest particle of an element which is capable of entering into a chemical reaction.

Atomic Energy: See Nuclear Energy.

Atomic Mass: The mass of an atom of an element compared with 1/16 the mass of an atom of an oxygen-16 atom.

Atomic Number: Number of protons in the nucleus, hence the number of positive charges on the nucleus. Also the number of electrons outside the nucleus of a neutral atom. Symbol: Z

Atomic Radiation: Radiation produced by energy changes in atomic nuclei or atomic electron clouds: ionizing radiation.

Atomic Reactor: See Nuclear Reactor.

Background: The counting rate or the ionizing radiation produced by cosmic radiation and naturally occurring trace amounts of radioactive elements.

Beta Particle: Charged particle emitted from the nucleus and having a mass and charge equal in magnitude to those of the electron.

Beta Ray: A stream of beta particles, more penetrating but less ionizing than alpha rays; a stream of high-speed electrons.

Betatron: A machine used to accelerate electrons.

Binding Energy: The energy that holds the nucleus together, it is quantitatively related to the difference in mass of the separate component parts and the actual mass of the nucleus.

Carcinogenic: Cancer producing.

Cell: Structural unit of plants and animals. Cells are composed of a nucleus surrounded by cytoplasm.

Chain Reaction: Any chemical or nuclear process in which some of the products of the process are instrumental in the continuation or magnification of the process.

Chemical Bonds: The forces holding together the atoms of a molecule or chemical compound.

Chromosome: Component of cell nucleus concerned with transmittal of heredity.

Connective Tissue: Tissue which supports and binds together other tissues.

Critical Size: For a fissionable material, the minimum amount of a material which will support a chain reaction.

Curie: Standard measure of rate of radioactive decay; the quantity of any radioactive nuclide in which the number of disintegrations per second is $3.700 \times 10^{10}$.

Cyclotron: A machine which accelerates charged particles by electric and magnetic forces.

Decay: Disintegration of the nucleus of an unstable element by the spontaneous emission of charged particles and/or photons.

Decay Time: See Half Life.

Densitometer: Instrument utilizing the photoelectric principle to determine the degree of opacity of developed photographic film.

Deuterium: A heavy isotope of hydrogen having one proton and one neutron in the nucleus; Symbol: D or ${}_1H^2$.

Deuteron: Nucleus of a deuterium atom, containing one proton and one neutron.

Dosimeter: Instrument used to detect and measure an accumulated dosage of radiation; usually a pocket electroscope.

Electron: Negatively charged particle which is a constituent of every atom. Unit of negative electricity equal to $4.80 \times 10^{-10}$ esu. Its mass is about 1/2000 of that of a proton.

Electron Cloud: The group of electrons surrounding an atomic nucleus and, with it, forming the neutral atom.

Electron Volt: Amount of energy gained by an electron in passing across a potential difference of 1 volt. Abbrev: ev. A million electron volts is abbreviated MEV.

Electroscope: An instrument used to measure cumulative exposure to ionizing radiation.

Electrostatic Unit of Charge: (esu), that quantity of electric charge which, when placed in a vacuum 1 cm distant from an equal and like charge, will repel it with a force of 1 dyne.

Element: A substance consisting of atoms of the same atomic (Z) number.

Enzyme: Biologic catalyst for facilitating digestive and metabolic processes.

Epithelium: Tissue covering outside of body or lining body tubes or externally opening cavities.

Equivalent Roentgen (e.r.): That amount of radiation other than X- or gamma which produces in air an amount of ionization equal to that produced by one roentgen of X- or gamma radiation.

Erythema: Reddening.

Erythrocyte: Red blood cell; primary purpose is to carry oxygen from the lungs to the other body tissues and carbon dioxide from the other tissues to the lungs.

External Radiation: Radiation entering the body from without.

Film Badge: Small piece of X-ray or similar photographic film enclosed in a lightproof paper usually crossed by lead or cadmium strips, carried in a small metal or plastic frame. The badge is used to estimate the amount of radiation to which an individual has been exposed.

Gamma Ray: Electromagnetic radiation emitted from the nucleus of a radioactive atom.

Geiger-Mueller (G-M) Counter: Highly sensitive instrument for detecting radiation.

Gene: Chromosome component transmitting separate hereditary trait.

Half Life: Time required for a radioactive substance to lose by decay 50% of its activity.

Half Thickness: Thickness of absorbing material necessary to reduce the intensity of radiation by one-half.

Hemopoietic System: The tissues of the body that produce blood cells: this includes the bone marrow, the spleen, and the lymphoid tissues.

Internal Radiation: Radiation arising from inside the body; as from radio-isotopes assimilated and contained within the tissues.

Ion: Atomic particle, atom, or chemical radical (group of chemically combined atoms) bearing an electrical charge either positive or negative, caused by an excess or deficiency of electrons.

Ion Chamber: Container of gas in which an electric field exists because of a system of charged electrodes.

Ionization: Act or result of any process by which a neutral atom or molecule acquires either a positive or a negative charge.

Ionizing Radiation: Radiation possessing sufficient energy to ionize the atoms or molecules absorbing it.

Isotope: One of two or more forms of an element having the same atomic number (nuclear charge) and hence occupying the same position in the periodic table. All isotopes are identical in chemical behavior, but are distinguishable by small differences in atomic weight. The nuclei of all isotopes of a given element have the same number of protons but differ in the number of neutrons.

Kev: Abbreviation for thousand electron volts. See Electron Volt.

Kinetic Energy: Energy possessed by a mass because of its motion.

LD - 50: The dose of radiation at which 50% of a given animal species will die, usually within 30 days. Mean lethal dose.

Leukemia: A cancerous condition characterized by marked and uncontrolled overproduction and abnormal production of white blood cells.

Leukocyte: White blood cell, primary purpose is to help combat infection.

Leukocytopenia: Condition of having abnormally few white blood cells in the circulating blood.

Lipoid Degeneration: Degeneration of cells or tissues characterized by presence of fatty substances.

Lymphocyte: White blood cell arising from lymph glands and lymph nodes. Lymphocytes are extremely radiosensitive.

Mass: Quantity of matter, popularly thought of as identical to "weight".

Mass Number: The number of nucleons in the nucleus of an atom. Symbol: A.

Mass Unit: Unit of mass, 1/16 the mass of an oxygen atom ($O^{16}$) taken as 16.00000. Abbrev: mu.

Maximum Permissible Dose: The amount of radiation which a normal human being may receive day-in-and-day-out without any harmful effects to himself becoming evident during his lifetime.

Mev: Abbreviation for million electron volts. See Electron Volt.

Microcurie: A millionth of a curie (37,000 disintegrations/sec.).

Millicurie: A thousandth of a curie.

Molecule: Orderly group of atoms joined together by chemical bonds. Some molecules are small and simple, such as water ($H_2O$): others are large and complex such as chlorophyll-a ($C_{55}H_{72}O_5N_4Mg$).

Necrosis: Death of a circumscribed portion of tissue.

Neutron: A nuclear particle with a mass approximately the same as that of a proton and electrically neutral; a constituent of the atomic nucleus. Its mass is 1.00893 mu.

Nuclear Energy: The energy released by fission or fusion of atomic nuclei.

Nuclear Fission: A special type of nuclear transformation characterized by the splitting of a nucleus into at least two other nuclei and the release of a relatively large amount of energy.

Nuclear Fusion: Act of coalescing two or more nuclei.

Nuclear Reactor: A device or machine for producing energy by fission or fusion of atomic nuclei.

Nucleon: Generic name for the constituent parts of the nucleus. At present applied to protons and neutrons, but will include any other particle found to exist in the nucleus.

Nucleus: Heavy central part of an atom in which most of the mass and the total positive electric charge are concentrated.

Periodic Table: An arrangement of the chemical elements to show resemblances among them with respect to their chemical properties. In this table the elements are arranged in rows by order of atomic number.

Photon: A quantity of energy emitted in the form of electromagnetic radiation such as radio waves, light, x-rays and gamma-rays.

Plasma: The fluid portion of unclotted blood.

Positron: Nuclear particle equal in mass to the electron and having an equal but opposite charge. Its mass is 0.000548 mu.

Potential Difference: Difference in potential between any two points in a circuit; work required to carry a unit positive charge from one point to another.

Proportional Counter: Gas-filled radiation detection tube in which the pulse produced is proportional to the number of ions formed in the gas by the primary ionizing particle.

Protium: The simplest atomic configuration consisting of one electron and one proton. An isotope of hydrogen.

Proton: Nuclear particle with a positive electric charge equal numerically to the charge of the electron and having a mass of 1.007575 mu.

Protoplasm: The jelly-like material which makes up living cells.

Radiation: Propagation of energy through space; an electromagnetic wave or rapidly moving atomic or subatomic particle.

Radiation Sickness: The group of symptons developed consequent to an overexposure to ionizing radiation: symptons include weakness, nausea, vomiting, diarrhea, leukocytopenia, anemia, and spontaneous bleeding.

Radioactivity: Process whereby unstable nuclei undergo spontaneous atomic disintegration with liberation of energy, generally resulting in the formation of new elements. The process is accompanied by the emission of one or more types of radiation, such as alpha particles, beta particles, and gamma radiation.

Radioisotope: A radioactive isotope.

Radiological Health: The public health aspects of the use of ionizing radiation.

Roentgen: Standard unit of absorption of X- and gamma radiation: quantity of X- or gamma radiation such that the associated corpuscular emission per 0.0012938 of air (dry and at standard temperatures and pressure) produces, in air, ions carrying 1 electrostatic unit of quantity of electricity of either sign.

Roentgen Equivalent Man (rem): That quantity of radiation of any type which when absorbed by man produces a biologic effect equivalent to that produced by the absorption of one roentgen of X- or gamma radiation.

Roentgen Equivalent Physical (rep): That amount of ionizing radiation which, in tissue, produces the same amount of ionization as that produced by one roentgen in air: the dose of radiation (other than that covered by definition of the roentgen) which produces energy absorption of 93 ergs. per gram of tissue.

SD - 50: The dose of radiation at which 50% of a given animal species will develop radiation sickness.

Sexual Cell: Reproductive cell: egg or sperm cell.

Somatic Cell: Body cell.

Specific Ionization: The number of ionizations or ion pairs produced in air per centimeter of radiation path length. A mechanism for comparing the ionizing abilities of radiations.

Tenth Value Layer: That amount of absorber which decreases the intensity of radiation to one tenth its original value.

Tissue: Group of similar cells performing a specialized function.

Tritium: An isotope of hydrogen having 1 electron, 1 proton and 2 neutrons.

Valence Electron: Electron which is gained, lost, or shared in a chemical reaction.

Van de Graaff Accelerator: A machine using static electricity to accelerate charged particles.

X-ray: A penetrating electromagnetic radiation similar to gamma radiation. This radiation is produced as a result of sudden decrease in electron energy.

## Appendix B. List of the Elements

| Atomic Number | Element | Symbol | Chemical mass number |
|---|---|---|---|
| 0 | Neutron | n | 1 |
| 1 | Hydrogen | H | 1 |
| 2 | Helium | He | 4 |
| 3 | Lithium | Li | 7 |
| 4 | Beryllium | Be | 9 |
| 5 | Boron | B | 11 |
| 6 | Carbon | C | 12 |
| 7 | Nitrogen | N | 14 |
| 8 | Oxygen | O | 16 |
| 9 | Fluorine | F | 19 |
| 10 | Neon | Ne | 20 |
| 11 | Sodium | Na | 23 |
| 12 | Magnesium | Mg | 24 |
| 13 | Aluminum | Al | 27 |
| 14 | Silicon | Si | 28 |
| 15 | Phosphorus | P | 31 |
| 16 | Sulfur | S | 32 |
| 17 | Chlorine | Cl | 35 |
| 18 | Argon | A | 40 |
| 19 | Potassium | K | 39 |
| 20 | Calcium | Ca | 40 |
| 21 | Scandium | Sc | 45 |
| 22 | Titanium | Ti | 48 |
| 23 | Vanadium | V | 51 |
| 24 | Chromium | Cr | 52 |
| 25 | Manganese | Mn | 55 |
| 26 | Iron | Fe | 56 |
| 27 | Cobalt | Co | 59 |
| 28 | Nickel | Ni | 59 |
| 29 | Copper | Cu | 64 |
| 30 | Zinc | Zn | 65 |
| 31 | Gallium | Ga | 70 |
| 32 | Germanium | Ge | 73 |
| 33 | Arsenic | As | 75 |
| 34 | Selenium | Se | 79 |
| 35 | Bromine | Br | 80 |
| 36 | Krypton | Kr | 84 |
| 37 | Rubidium | Rb | 85 |
| 38 | Strontium | Sr | 88 |
| 39 | Yttrium | Y | 89 |

Appendix B. (continued)

| Atomic Number | Element | Symbol | Chemical mass number |
|---|---|---|---|
| 40 | Zirconium | Zr | 91 |
| 41 | Niobium | Nb | 93 |
| 42 | Molybdenum | Mo | 96 |
| 43 | Technetium | Te | 99 |
| 44 | Ruthenium | Ru | 102 |
| 45 | Rhodium | Rh | 103 |
| 46 | Palladium | Pd | 107 |
| 47 | Silver | Ag | 108 |
| 48 | Cadmium | Cd | 112 |
| 49 | Indium | In | 115 |
| 50 | Tin | Sn | 119 |
| 51 | Antimony | Sb | 122 |
| 52 | Tellurium | Te | 128 |
| 53 | Iodine | I | 127 |
| 54 | Xenon | Xe | 131 |
| 55 | Cesium | Cs | 133 |
| 56 | Barium | Ba | 137 |
| 57 | Lanthanum | La | 139 |
| 58 | Cerium | Ce | 140 |
| 59 | Praseodymium | Pr | 141 |
| 60 | Neodymium | Nd | 144 |
| 61 | Promethium | Pm | 147 |
| 62 | Samarium | Sm | 150 |
| 63 | Europium | Eu | 152 |
| 64 | Gadolinium | Gd | 157 |
| 65 | Terbium | Tb | 159 |
| 66 | Dysprosium | Dy | 162 |
| 67 | Holmium | Ho | 165 |
| 68 | Erbium | Er | 167 |
| 69 | Thulium | Tm | 169 |
| 70 | Ytterbium | Yb | 173 |
| 71 | Lutecium | Lu | 175 |
| 72 | Hafnium | Hf | 179 |
| 73 | Tantalum | Ta | 181 |
| 74 | Wolfram | W | 184 |
| 75 | Rhenium | Re | 186 |
| 76 | Osmium | Os | 190 |
| 77 | Iridium | Ir | 193 |
| 78 | Platinum | Pt | 195 |
| 79 | Gold | Au | 197 |
| 80 | Mercury | Hg | 201 |
| 81 | Thallium | Tl | 204 |

Appendix B. (continued)

| Atomic Number | Element | Symbol | Chemical mass number |
|---|---|---|---|
| 82 | Lead | Pb | 207 |
| 83 | Bismuth | Bi | 209 |
| 84 | Polonium | Po | 210 |
| 85 | Astatine | At | 218 |
| 86 | Radon | Rn | 222 |
| 87 | Francium | Fa | 223 |
| 88 | Radium | Ra | 226 |
| 89 | Actinium | Ac | 227 |
| 90 | Thorium | Th | 232 |
| 91 | Protactinium | Pa | 231 |
| 92 | Uranium | U | 238 |
| 93 | Neptunium | Np | 237 |
| 94 | Plutonium | Pu | 239 |
| 95 | Americium | Am | 241 |
| 96 | Curium | Cm | 242 |
| 97 | Berkelium | Bk | 244 |
| 98 | Californium | Cf | 246 |

Appendix C - Masses of the Known Isotopes from G. E. Chart, November, 1952*

| Element | Mass Numbers |
|---|---|
| Actinium | 222, 223, 224, 225, 226, [227], [228], 229, 230 |
| Aluminum | 24, 25, 26, 27, 28, 29 |
| Americium | 237, 238, 239, 240, 241, 242, 243, 244 |
| Antimony | 116, 117, 118, 119, 120, 121, 122, 123, 124, 125, 126, 127, 128, 129, 130, 131, 132, 133, 134 |
| Argon | 35, 36, 37, 38, 39, 40, 41, 42 |
| Arsenic | 70, 71, 72, 73, 74, 75, 76, 77, 78, 79 |
| Astatine | 202, 203, 204, 205, 206, 207, 208, 209, 210, 211, 212, 214, 215, 216, 217, [218] |
| Barium | 127, 128, 129, 130, 131, 132, 133, 134, 135, 136, 137, 138, 139, 140, 141, 142, 143, 144, 145 |
| Berkelium | 243, 244, 245 |
| Beryllium | 7, 8, 9, 10 |
| Bismuth | 197, 198, 199, 200, 201, 203, 204, 205, 206, 207, 209, [210], [211], [212], 213, [214] |
| Boron | 8, 9, 10, 11, 12 |
| Bromine | 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 87, 88, 89 |
| Cadmium | 105, 106, 107, 108, 109, 110, 111, 112, 113, 114, 115, 116, 117 |
| Calcium | 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49 |
| Californium | 244, 246 |
| Carbon | 10, 11, 12, 13, 14, 15 |
| Cerium | 133, 134, 135, 136, 137, 138, 139, 140, 141, 142, 143, 144, 145, 146 |
| Cesium | 127, 128, 129, 130, 131, 132, 133, 134, 135, 136, 137, 138, 139, 140, 141, 142, 143, 144, 145 |
| Chlorine | 33, 34, 35, 36, 37, 38, 39 |
| Chromium | 48, 49, 50, 51, 52, 53, 54 |
| Cobalt | 55, 56, 57, 58, 59, 60, 61, 62, 64 |
| Copper | 58, 59, 60, 61, 62, 63, 64, 65, 66, 67 |
| Curium | 238, 239, 240, 241, 242, 243, 244 |
| Dysprosium | 156, 158, 159, 160, 161, 162, 163, 164, 165, 166 |
| Erbium | 161, 162, 163, 164, 165, 166, 167, 168, 169, 170, 171 |
| Europium | 144, 145, 146, 147, 148, 149, 150, 151, 152, 153, 154, 155, 156, 157, 158, 159 |
| Fluorine | 17, 18, 19, 20 |
| Francium | 211, 212, 218, 219, 220, 221, 222, [223] |
| Gadolinium | 148, 149, 150, 151, 152, 153, 154, 155, 156, 157, 158, 159, 160, 161 |

* Stable Isotope Mass Numbers: Underlined
Naturally Occurring Radioisotopes Boxed: ☐
Artificial Radioisotopes: Roman

Appendix C - Masses of the Known Isotopes from G. E. Chart, November, 1952*

| Element | Mass Numbers |
|---|---|
| Gallium | 65, 66, 67, 68, 69, 70, 71, 72, 73 |
| Germanium | 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78 |
| Gold | 188, 191, 192, 193, 194, 195, 196, 197, 198, 199, 200, 201, 203 |
| Hafnium | 170, 171, 172, 173, 174, 175, 176, 177, 178, 179, 180, 181 |
| Helium | 3, 4, 5, 6 |
| Holmium | 160, 161, 162, 163, 164, 165, 166, 169 |
| Hydrogen | 1, 2, 3 |
| Indium | 107, 108, 109, 110, 111, 112, 113, 114, 115, 116, 117, 118, 119 |
| Iodine | 120, 121, 122, 123, 124, 125, 126, 127, 128, 129, 130, 131, 132, 133, 134, 135, 136, 137, 138, 139 |
| Iridium | 187, 188, 189, 190, 191, 192, 193, 194, 195, 197 |
| Iron | 52, 53, 54, 55, 56, 57, 58, 59, 60 |
| Krypton | 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 97 |
| Lanthanum | 131, 132, 133, 134, 135, 136, 137, 138, 139, 140, 141, 142, 143, 144, 145 |
| Lead | 198, 199, 200, 201, 203, 204, 206, 207, 208, 209, [210], [211], [212], [214] |
| Lithium | 5, 6, 7, 8, 9 |
| Lutecium | 170, 171, 172, 173, 174, 175, [176], 177, 178, 179 |
| Magnesium | 23, 24, 25, 26, 27 |
| Manganese | 51, 52, 54, 55, 56 |
| Mercury | 190, 191, 192, 193, 195, 196, 197, 198, 199, 200, 201, 202, 203, 204, 205 |
| Molybdenum | 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 101, 102, 105 |
| Neodymium | 138, 139, 140, 141, 142, 143, 144, 145, 146, 147, 148, 149, 150, 151 |
| Neon | 19, 20, 21, 22, 23 |
| Neptunium | 231, 232, 233, 234, 235, 236, 237, 238, 239, 240, 241 |
| Neutron | 1 |
| Nickel | 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66 |
| Niobium | 90, 91, 92, 93, 94, 95, 96, 97, 98, 99 |
| Nitrogen | 12, 13, 14, 15, 16, 17 |
| Osmium | 182, 183, 184, 185, 186, 187, 188, 189, 190, 191, 192, 193, 194 |
| Oxygen | 14, 15, 16, 17, 18, 19 |

* Stable Isotope Mass Numbers: Underlined
Naturally Occurring Radioisotopes Boxed: ☐
Artificial Radioisotopes: Roman

Appendix C - Masses of the Known Isotopes from G. E. Chart, November, 1952*

| Element | Mass Numbers |
|---|---|
| Palladium | 98, 99, 100, 101, 102, 103, 104, 105, 106, 107, 108, 109, 110, 111, 112 |
| Phosphorus | 29, 30, 31, 32, 34 |
| Platinum | 190, 191, 192, 193, 194, 195, 196, 197, 198, 199 |
| Plutonium | 232, 234, 235, 236, 237, 238, 239, 240, 241, 242, 243 |
| Polonium | 200, 201, 202, 203, 204, 205, 206, 207, 208, 209, [210], [211], [212], 213, [214], [215], [216], 217, [218] |
| Potassium | 37, 38, 39, [40], 41, 42, 43, 44 |
| Praseodymium | 138, 139, 140, 141, 142, 143, 144, 145, 146 |
| Promethium | 141, 143, 144, 145, 146, 147, 148, 149, 150, 151 |
| Protactinium | 226, 227, 228, 229, 230, [231], 232, 233, [234], 235 |
| Radium | 213, 219, 220, 221, 222, [223], [224], 225, [226], 227, [228], 229, 230 |
| Radon | 209, 210, 211, 212, 215, 216, 217, 218, [219], [220], [222] |
| Rhenium | 182, 183, 184, 185, 186, [187], 188, 189, 190, 191 |
| Rhodium | 99, 100, 101, 102, 103, 104, 105, 106, 107, 108 |
| Rubidium | 81, 82, 83, 84, 85, 86, [87], 88, 89, 90, 91, 92, 93, 94, 97 |
| Ruthenium | 94, 95, 96, 97, 98, 99, 100, 101, 102, 103, 104, 105, 106, 107 |
| Samarium | 143, 144, 145, 147, 148, 149, 150, 151, 152, 153, 154, 155, 156 |
| Scandium | 41, 43, 44, 45, 46, 47, 48, 49 |
| Selenium | 70, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84 |
| Silicon | 27, 28, 29, 30, 31 |
| Silver | 102, 104, 105, 106, 107, 108, 109, 110, 111, 112, 113, 114, 115 |
| Sodium | 20, 21, 22, 23, 24, 25 |
| Strontium | 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 97 |
| Sulfur | 31, 32, 33, 34, 35, 36, 37 |
| Tantalum | 176, 177, 178, 179, 180, 181, 182, 183, 185 |
| Technetium | 92, 93, 94, 95, 96, 97, 98, 99, 100, 101, 102, 105 |
| Tellurium | 117, 118, 119, 120, 121, 122, 123, 124, 125, 126, 127, 128, 129, 130, 131, 132, 133, 134 |
| Terbium | 149, 151, 153, 154, 155, 156, 157, 158, 159, 160, 161, 163 |
| Thallium | 198, 199, 200, 201, 202, 203, 204, 205, [206], [207], [208], 209, [210] |
| Thorium | 223, 224, 225, 226, [227], [228], 229, [230], [231], [232], 233, [234], 235 |

*Stable Isotope Mass Numbers: Underlined
Naturally Occurring Radioisotopes Boxed: [ ]
Artificial Radioisotopes: Roman

Appendix C - Masses of the Known Isotopes from G. E. Chart, November, 1952*

| Element | Mass Numbers |
|---|---|
| Thulium | 166, 167, 168, 169, 170, 171, 172, 175 |
| Tin | 108, 111, 112, 113, 114, 115, 116, 117, 118, 119, 120, 121, 122, 123, [124], 125, 126, 127, 128 |
| Titanium | 43, 45, 46, 47, 48, 49, 50, 51 |
| Uranium | 227, 228, 229, 230, 231, 232, 233, [234], [235], 236, 237, [238], 239, 240 |
| Vanadium | 47, 48, 49, 51, 52 |
| Wolfram | 176, 177, 178, 179, 180, 181, 182, 183, 184, 185, 186, 187, 188 |
| Xenon | 121, 122, 123, 124, 125, 126, 127, 128, 129, 130, 131, 132, 133, 134, 135, 136, 137, 138, 139, 140, 141, 143, 144, 145 |
| Ytterbium | 166, 168, 169, 170, 171, 172, 173, 174, 175, 176, 177, 180 |
| Yttrium | 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 97 |
| Zinc | 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72 |
| Zirconium | 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97 |

*Stable Isotope Mass Numbers: Underlined
Naturally Occurring Radioisotopes Boxed: ▭
Artificial Radioisotopes: Roman

## Appendix D

### Comparison of Relative Weights and Speeds of Shotgun Pellets and Alpha Particles

Number 5 Shotgun Pellets are approximately 0.12 inches in diameter and weigh about 0.005 ounces (2.5 grains). They leave the muzzle of a 12 gauge shotgun with an average velocity of 860 feet per second.

Alpha Particles weigh about $6.6 \times 10^{-24}$ grams (4 mass units) and those having 1 mev energy travel with a velocity approximating 230 million feet (44,000 miles) per second.

An average sized man weighs about 150 pounds or 2400 ounces.

A protein molecule (hemoglobin weighs about $1.1 \times 10^{-19}$ grams —— 68,000 mass units).

Therefore, the ratio of the weight of a #5 pellet to the weight of a man is about:

$$\frac{0.005 \text{ ounces}}{2400.000 \text{ ounces}} = \frac{1}{480,000} \qquad \text{(A)}$$

The ratio of the weight of an alpha particle to the weight of a hemoglobin molecule is about:

$$\frac{6.6 \times 10^{-24} \text{ grams}}{1.1 \times 10^{-19} \text{ grams}} = \frac{1}{17,000} \qquad \text{(B)}$$

The ratio of the relative weight of the alpha particle and the hemoglobin molecule to that of the #5 shot and the man is about:

$$\frac{B}{A} = \frac{\frac{1}{17,000}}{\frac{1}{480,000}} = \frac{28}{1} \qquad \text{(C)}$$

And, the ratio of the speed of the alpha particle to that of the #5 shot is about:

$$\frac{230,000,000 \text{ ft/sec}}{860 \text{ ft/sec}} = \frac{270,000}{1} \qquad \text{(D)}$$

## Appendix E. Comparison of Properties of Selected Radioisotopes

| Isotope | Half-Life[a] | Grams per Curie | Maximum permissible amount in body (gms.)[b] |
|---|---|---|---|
| Uranium-238 | 4,510,000,000 yrs. | 3,000,000 | Not internal hazard[c] |
| Potassium-40 | 1,200,000,000 yrs. | 130,000 | Not internal hazard[c] |
| Uranium-235 | 710,000,000 yrs. | 470,000 | Not internal hazard[c] |
| Cesium-135 | 3,000,000 yrs. | 1,100 | - - - |
| Plutonium-239 | 24,300 yrs. | 16 | 0.6 Millionth |
| Carbon-14 | 5,580 yrs. | 0.22 | 55 Millionths |
| Radium-226 | 1,620 yrs. | 1.0 | 0.1 Millionth |
| Strontium-90 | 20 yrs. | 0.005 0 | 5 Billionths |
| Hydrogen-3 | 12.4 yrs. | 0.000 10 | 1.0 Millionth |
| Cobalt-60 | 5.2 yrs. | 0.000 87 | 2.6 Billionths |
| Calcium-45 | 152 days | 0.000 052 | 3.4 Billionths |
| Polonium-210 | 138 days | 0.000 22 | 1.1 Trillionths |
| Strontium-89 | 54 days | 0.000 037 | 74 Trillionths |
| Iron-59 | 45 days | 0.000 020 | 20 Billionths |
| Phosphorus-32 | 14.3 days | 0.000 003 5 | 35 Trillionths |
| Iodine-131 | 8.14 days | 0.000 008 2 | 2.5 Trillionths |
| Radon-222 | 3.825 days | 0.000 006 5 | - - - |
| Sodium-24 | 15.0 hours | 0.000 000 12 | 1.8 Trillionths |
| Iron-52 | 7.8 hours | 0.000 000 13 | - - - |
| Argon-41 | 1.82 hours | 0.000 000 024 | 0.7 Trillionth |
| Nitrogen-16 | 7.3 sec. | 0.000 000 000 010 | - - - |
| Polonium-212 | 0.000 000 3 sec. | 0.000 000 000 000 000 000 0056 | - - - |

[a] From G.E. Chart of the Nuclides; November, 1952.

[b] Based on 150 lb. man and estimates published in the "Recommendations of the International Commission on Radiological Protection and of the International Commission on Radiological Units", U. S. Department of Commerce, National Bureau of Standards, Handbook 47, June 29, 1951 and in "Maximum Permissible Amounts of Radioisotopes in the Human Body and Maximum Permissible Concentrations in Air and Water", U. S. Department of Commerce, National Bureau of Standards, Handbook 52, March 20, 1953

[c] Not internal radiation hazard; is a chemical poison, however.